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Final Report

Laser-Hologram Multicolor Moving Map Display System

Contract No. N62269-70-C-0080

Prepared for

Naval Air Development Center
Naval Air Systems Command
Department of the Navy
Warminster, Pennsylvania

Prepared by

RCA Advanced Technology ~~Laboratories~~, — Burlington, Mass
Government and Commercial Systems Hq
RCA
Burlington, Massachusetts

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Laser-Hologram Multicolor Moving Map Display System

By

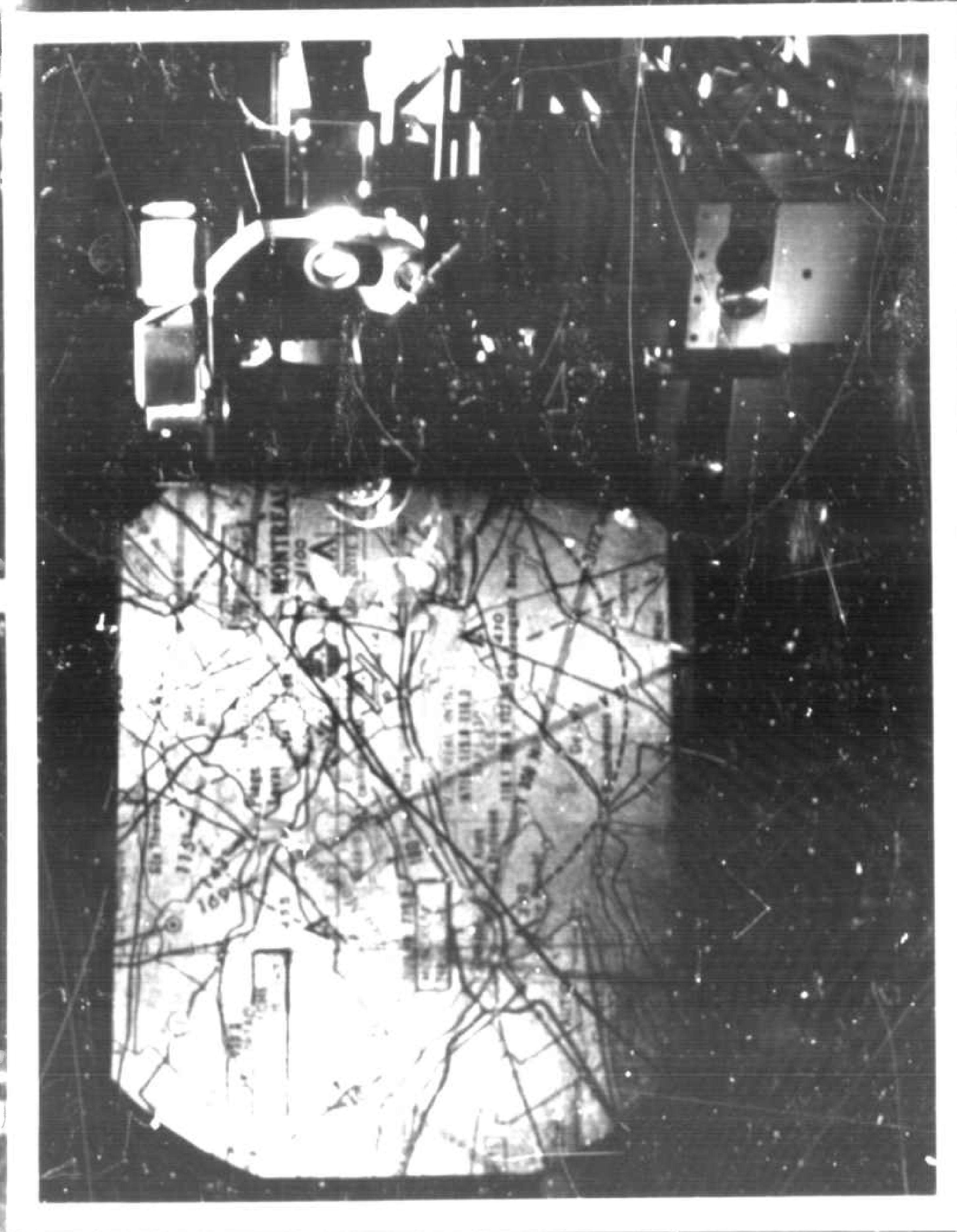
G. T. Burton
B. R. Clay
R. F. Croce
D. A. Gore

FOREWORD

This report was prepared by the Advanced Technology Laboratories (Burlington, Mass.) of the Government and Commercial Systems division, RCA, under Navy contract N62269-70-C-0080 entitled "Laser-Hologram Multicolor Moving Map Display System." The work was administered by K.D. Quiring and K.W. Priest, Naval Air Development Center, Warminster, Pennsylvania.

The work was carried out under the direction of F.E. Shashoua, Manager, and G.T. Burton, Leader. B.R. Clay was the principal investigator; major technical contributions were made by R.F. Croce and D.A. Gore.

This report is the final technical report and covers the work performed during the period from August 29, 1969 to August 29, 1970.



ABSTRACT

This report describes the results of the work performed under an exploratory development program designed to establish the techniques required to present a multicolor moving map display to a pilot in an aircraft cockpit environment. A system for producing a full color display 6 inches in diameter with the provision for translating and rotating the image has been postulated and its feasibility demonstrated. Methods of presenting symbols on the display have also been postulated.

During the course of the program, a holographic recording technique was selected which allowed playback of the information using white light sounds. A storage material was selected and a large volume duplication technique described. Tradeoffs were established to define the optimum method for providing display motion and symbol insertion.

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Section I

SUMMARY AND INTRODUCTION

A. STATEMENT OF TASK

High performance aircraft present the problem of providing navigational information to the pilot (or navigator) in a quick, clear and concise manner; in particular, a significant need exists for a multicolor display in a form suitable for aircraft use.

This report describes the results of the work performed under an exploratory development program designed to establish the techniques required to present a multicolor moving map display to a pilot in an aircraft cockpit environment. A system for producing a full color display, 6 inches in diameter, with the provision for translating and rotating the displayed image has been postulated and its feasibility demonstrated. Methods of presenting symbols on the display have also been developed.

B. ADVANTAGES OF HOLOGRAPHIC APPROACH

Of particular concern has been the use of holographic techniques to provide a method of information storage and retrieval which for the cockpit application provide advantages not found in more conventional methods of information storage. For example, the potential advantages to be gained by using holography as compared to microfilm storage include:

(1) Storage of color information on a medium which is durable, archival, and easily and inexpensively duplicated.

(2) High degree of immunity to scratches and abrasions at information storage densities comparable to high reduction microfilm systems.

(3) Utilization of lens systems which are less complex and easier to align than those available for use with more conventional high density storage display systems.

(4) Recording of information in a form (phase) and on a storage medium which does not absorb energy and can consequently control high optical energy densities without destroying the storage medium. (A storage medium of this type is essential for the development of a high brightness, direct-view display using high density storage medium.)

(5) Recording of data block information (retrieval information) such that a stationary image is formed in space and is self-registering on a readout sensor.

C. FEASIBILITY INVESTIGATION AND EVALUATION

A system having the performance characteristics tabulated in Table I was postulated and evaluated under this program. In the evolution of this system, four areas of investigation were pursued. A brief summary of the approach and recommendations in each area is presented in the following paragraphs.

1. Recording Technique

Various schemes were considered for recording and projecting holograms to provide a map display in full color. The multiple-exposure quasi-focused image technique using white light sources for reconstruction was selected as the optimum technique for this program and is recommended for inclusion in future models. This technique and the reasons leading to its selection are described in detail in Section III.

Techniques were also considered for storing data block information. A Fraunhofer hologram recorded over the map information is recommended for storing data block information. This technique and the reasons leading to its selection are described in Section IVE.

2. Recording Material

A laboratory investigation was performed to select recording materials for dense packing of maps in holographic form which upon restoration produce a color display having high brightness. A photoresist material is recommended as the original recording material. This material is a phase material; it allows inexpensive duplication of the holograms using a nickel plating technique to generate a master which can, in turn, be used to generate copies on a vinyl material. A survey of possible recording materials, a description of the selected recording material, and the method of generating copies are presented in Section IVD.

3. Map Motion

Methods of translating the displayed image and rotating the image about the display center were developed. Translation of the image is provided by translating the hologram; image rotation is accomplished by the insertion of a rotating prism in the optical path. The methods of image rotation and translation are discussed in Section IVF.

4. Symbology

Techniques which allow the introduction of symbols on the display were investigated. The symbology requirement can be approached in two ways: (1) generation and positioning of the symbols by the pilot during flight; and (2) annotation of

TABLE I. CHARACTERISTICS OF MULTICOLOR MOVING MAP DISPLAY

Color fidelity	Equivalent to existing aerial maps; a color balance between red, blue and green of ±10% will be maintained at various luminance levels.
Resolution	10 lp/mm, 65% response
Viewing area	Circular, 6-in diameter
Screen brightness	Acceptable for comfortable viewing in a well lighted room (250 lumens/ft^2 ambient incident on viewing screen) when used with a directional viewing screen. Provision will be made for reducing the display intensity from full brightness to zero intensity.
Viewing screen	Directional specular antireflective. The screen will provide an eye relief area of 2 in x 6 in minimum at a viewing distance of 30 in.
Display Unit Size Weight	8 in x 8 in x 24 in maximum 35 lb maximum
Power Supply Size Weight	2 ft^3 maximum 45 lb maximum
Reconstruction optical sources	Three filtered white light sources
Storage medium	Vinyl tape; embossed from nickel master, stripped from photoresist
Storage density	Information sufficient for reconstruction of a 12.5-in x 12.5-in full-color chart segment will be contained in a holographic storage area with the maximum dimensions of 0.5 in x 0.5 in.
Address indexing code	8-bit digital code overlayed as a Fraunhofer hologram on the chart information
Address pick-up	8-element linear diode array
X-Y Position	Continuous motion over a range of ±3.5 in in North-South and East-West directions

TABLE I. CHARACTERISTICS OF MULTICOLOR MOVING MAP DISPLAY (Cont'd)

Rotation	Full 360° image rotation
Set-up time	Less than five minutes
Power requirements	2 kVA maximum, 115V, 60 Hz, single phase
Operating stability	200 hours, without adjustments which are inaccessible during equipment operation
Operating life	1000 hours minimum with reasonable servicing and replacement of parts

symbols on the display information prior to flight. Representative systems are described in Section IVG. Further investigation is recommended in this area to ensure the selection of an optimum technique.

The holographic approach to a full-color moving display of aerial charts offers advantages not found in other display approaches. The development of a cockpit display unit based on the recommended RCA design is feasible at this time.

D. REPORT CONTENTS

The advantages of holographic recording are discussed in Section II. A complete system description and its operating characteristic are presented in Sections III and IV; this system is recommended by RCA for future development. Section V considers the possible field utilization of the recommended systems. Section VI describes the laboratory setup used to evaluate the parameters of the storage and display system.

Appendices are included which present a specification for a laboratory model, a brief discussion of various techniques of recording and reconstructing holograms, a plan for the development of a prototype unit, and descriptions of the demonstrations performed on the contract.

Section II

HOLOGRAPHY AND ITS ADVANTAGES

A. HOLOGRAPHIC RECORDING CHARACTERISTICS

Holography is a technique for recording and at a later time reconstructing an optical wavefront. The recording operation is accomplished by storing an interference pattern — a hologram — developed between the wavefront to be recorded and a reference wavefront derived from a common coherent source (a laser). The interference pattern is recorded on a storage medium which responds to the intensity of the optical signal falling on it. By recording in this fashion, the recording medium stores both phase and intensity information. Sufficient information is preserved by recording both these parameters to allow complete reconstruction of the recorded wavefront. Reconstruction is accomplished by illuminating the stored interference pattern with a reconstruction wavefront identical to the reference wavefront used to produce the interference pattern.

Holography differs from conventional photography in that its ability to record an optical wavefront allows (at least in theory) the recording of information at any location within an optical system; whereas conventional photography requires that recording be done in the image plane to afford maximum preservation of information. This difference results from the fact that only intensity information is recorded in the photographic process while both phase and intensity information are recorded in the holographic process.

It is this property, the principle of wavefront reconstruction, which allows restoration of three-dimensional images from a two-dimensional storage plane. But since this study has been concerned with the storage and reconstruction of two-dimensional color maps and not three-dimensional images, the question arises of the need or desirability of holographic storage. This is particularly pertinent in light of the additional complexities associated with holographic recording. First, in order to record holographically, a coherent source, a laser, must be employed to allow generation of the interference pattern which records the phase information. Second, the recording must be accomplished in a vibration-free environment. The interference pattern is destroyed if, during recording, motions of the order of fractions of a wavelength are developed between the object beam and reference beam at the recording plane.

The advantages which offset these difficulties, however, are numerous; the more significant ones are discussed in the following paragraphs.

B. ADVANTAGES OF HOLOGRAPHIC RECORDING

1. Inexpensive Replication

The use of surface effect recording such as that produced by the photoresist materials allows the use of an inexpensive method of replicating the holograms. This process is discussed in detail in Section IV D. The basic process, however, is one of forming a hologram on a photoresist material, nickel plating the material, stripping off the nickel, and using the nickel master to make many copies by embossing the relief image into an inexpensive material such as the vinyl material used to wrap meat in a supermarket. In the method of holographic storage recommended for this program, the holograms are reconstructed in the reflective mode. To accomplish this type of reconstruction, the holograms are aluminum plated. During restoration, the optical signal is not transmitted through the base material and consequently the uniformity of this material is not critical.

2. Durable Base Material

The base material which has been selected for replication of the hologram is inexpensive, highly durable, and possesses a high degree of immunity to scratches and abrasions as compared to conventional hardened photographic emulsions. The material is also unaffected by moisture or immersion in water.

3. Full-Color Restoration from a Common Storage Area

The inexpensive vinyl material can be used to store multiple images in a common area. The techniques to accomplish this are described in detail in Sections III and IV. For the application of this contract, full-color restoration is accomplished by storing three holograms in a common storage area. Three color separations - one for the red, a second for the green, and a third for the blue - are stored one on top of another. The method of recording is such that on playback, three filtered white light sources can be used to establish three reconstruction wavefronts. The three sources are filtered to produce, respectively, red, green and blue reconstruction wavefronts. The three wavefronts impinge on the common holographic area and are reflected to form the full-color image.

4. Rapid Retrieval Capability

As was stated earlier, holography is a means of recording an optical wavefront. We have the option of entering at any location in an optical system and recording the wavefront that exists at that point. It is possible to enter the optical system and record the wavefront in such a fashion that upon reconstruction the location of the storage medium illuminated by a fixed reconstruction wave no longer influences the

position of the image formed in space. A hologram which possesses this property is the Fraunhofer hologram. This type hologram is recorded over the three color separation holograms to store data block information associated with the stored map. The production of a stationary image in space independent of the position of the hologram provides information which can be used to control a rapid retrieval system. The same technique can also be used to provide other information concerning the particular map displayed.

5. High Display Brightness

In conventional photography, an image is formed by collecting and imaging energy reflected from or transmitted through the storage medium. Information is impressed on the reflected or transmitted wavefront by absorbing energy from the optical signal incident on the storage medium. For a high density, direct-view storage system, the display brightness is limited by the amount of optical power that can be absorbed by the storage medium without causing the medium to overheat to the degree that information is destroyed or distorted.

In holographic recording, information may be recorded on a medium which allows the wavefront to be reconstructed by effecting the phase distribution of the reconstruction wavefront rather than by effecting its energy distribution. Phase recording modulates the phase distribution of the reference wavefront as it is reflected from or transmitted through the storage medium. This is accomplished by producing different path lengths for different portions of the optical wavefront. This method of recording allows a virtually unlimited light flux to be gated by the hologram since this form of wavefront modulation involves essentially no power loss in the storage medium.

Phase holograms may be recorded so as to obtain the optical path length modulation in one of three ways: (1) as refractive index variations in the material, (2) as surface depth variations, or (3) as a combination of the two. The selection of the photosensitive material determines the effect to be utilized. For example, ferroelectric crystals and dichromated gelatines record refractive index variations, photoresists record surface variations, and bleached silver halide emulsions record both surface variations and refractive index variations.

6. Reconstruction With Simple Optics

Another major advantage of holography is the ability of the system to provide reconstruction of the information with an optical system of considerably less complexity than for an equivalent microfilm system. This is particularly true when considering the depth of focus. In order to effectively utilize a microfilm system, very low f/number optics with associated narrow depths of field must be employed. This is necessary to collect as much of the optical energy as possible to provide an acceptably bright display. However because it is a technique for recording wavefronts, a holographic system can operate with very high effective f/numbers resulting in large depths of field. Consequently a focusing operation is much easier to effect than in a comparable microfilm system.

Section III

STORAGE TECHNIQUE

A. GENERAL

There are two methods of reconstructing holographically stored images and presenting them to a viewer. First, the image may be constructed as either a real or a virtual image which is directly viewed by the observer. (In the case of the virtual image, the resulting beam is intercepted by the viewer's eye. For a reconstruction of a real image, the image is formed on a screen having gain in the direction of the observer.) The second method forms the image on the transducer surface of a television camera tube for interrogation. The interrogated image is then displayed on a CRT for viewing by the observer.

Both forms of display were considered for application to this program, in which the primary goal is to develop a display in color which can be viewed in the presence of high ambient illumination. After considering a variety of television-type systems, it was concluded that they are not practical for this application. The display technique should be capable of filling a 6-inch circular display area with an image having a resolution of at least 12 lp/mm (1840 lp per picture height). This order of resolution is barely possible for a high-resolution black-and-white monitor; it is not practical for existing color television display systems using conventional techniques or for techniques which appear practical in a cockpit display.

The alternatives of direct-view displays were next considered. It early became apparent that the use of laser sources for the generation of a display of adequate brightness was not practical. The size, weight and primary power requirements of the laser heads to produce full-color restoration was prohibitive for a cockpit environment. Consequently, emphasis was placed on techniques which allow holographic image reconstruction using filtered white-light sources.

A variety of holographic techniques were considered for storing the map information. Primary emphasis was placed on holographic forms which allow image motion proportional to the motion of the hologram while at the same time allowing reconstruction using filtered white light (high-intensity arc lamp) sources. Of the holographic forms investigated (Fresnel, Fraunhofer, Fourier transform, focused image and quasi-focused image; see Appendix B), all but the Fraunhofer and the Fourier transform holograms can be implemented with an image motion proportional to the motion of the holographic medium. Of the remaining three forms, only the focused image and

quasi-focused image forms can be constructed efficiently using incoherent white-light sources (although inefficient white-light reconstruction has been demonstrated for both the Fresnel and Fourier transform holograms). *

The focused image hologram although ideal for white-light reconstruction is a holographic form which possesses limited redundancy. When the hologram is being formed, a point on the object is imaged to a small spot on the holographic plane. The refraction patterns developed between this spot and the reference beam form localized fring patterns in the mediums, allowing holographic reconstruction. If the film is scratched or abraded in the area of the recorded spot, the information is obscured by the imperfection. The severity of this problem is relaxed by utilizing a quasi-focused image form of holography. In this case, the holographic recording plate is moved out of the image plane. A point in the image plane is now formed on the storage plate as a large defocused spot. This is recorded as an interference pattern between the defocused spot and a reference beam. This interference pattern can also be used in conjunction with a white-light source to form an image. The advantage gained is that the energy from a point in the image is distributed over a large area on the recording plane; consequently, it has a reduced sensitivity to distortion of the image by imperfection in the recording such as dirt, scratches and abrasions. The nature of the introduced redundancy is discussed later in this section.

The quasi-focused image hologram may be formed as a surface or relief hologram with the information stored either as absorption or refractive index variations in the medium. For the purposes of this program, phase recording was employed.

Color information is stored in this holographic form by utilizing three color separation negatives of the full-color object. The three separations are recorded using a coherent source on the common area of the holographic plate but at different reference beam angles as discussed in Section III G. Reconstruction is accomplished by utilizing three white-light sources filtered to allow passage of the red, blue and green portions of the spectrum, respectively. An experimental setup (see Section VI) was established to evaluate this form of recording and restoration.

B. QUASI-FOCUSED IMAGE HOLOGRAMS

Figure 1 is a diagram of a system which is capable of recording and playing back focused and quasi-focused image holograms. A truly focused image hologram is formed by allowing a focused image of the object to be stored to interfere with a

*The Lippman-Bragg hologram is extremely effective, approaching 96 percent in white light. It is, however, a volume hologram and as such does not lend itself to inexpensive replication techniques. It must also be recorded on crystal material which cannot be produced with any degree of consistency at this time. (See discussion on volume materials in Section IVD.)

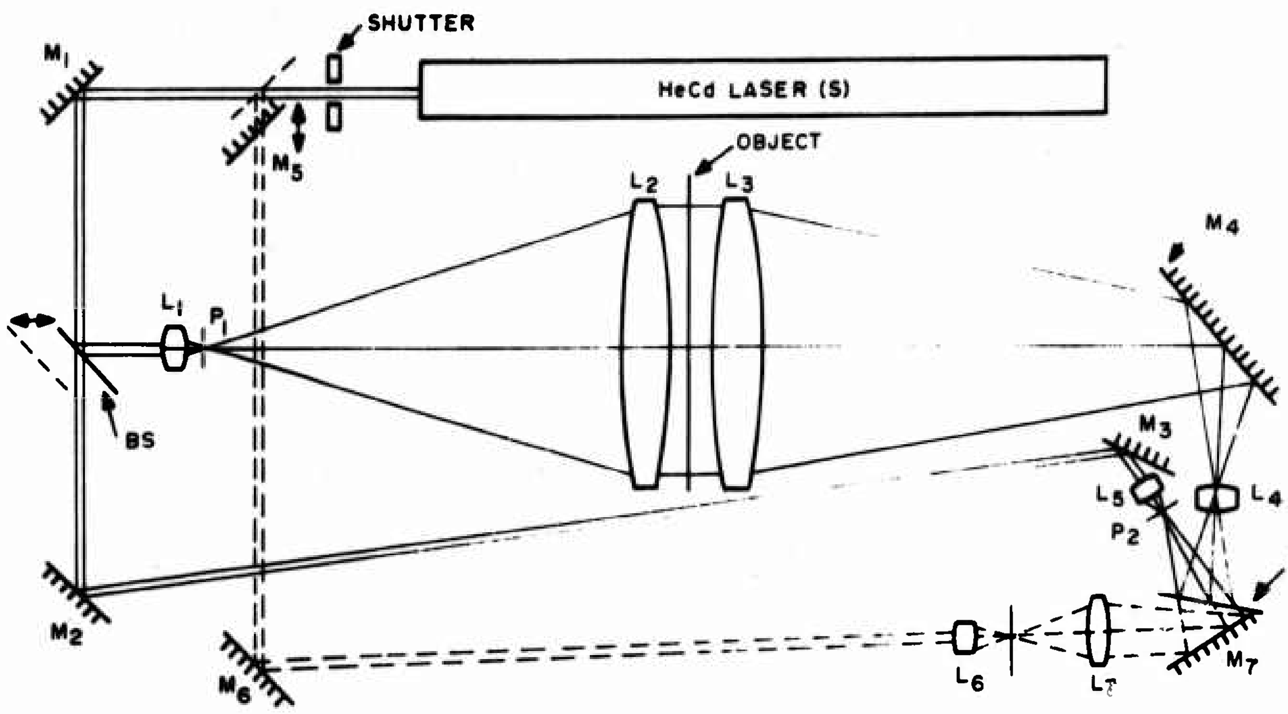
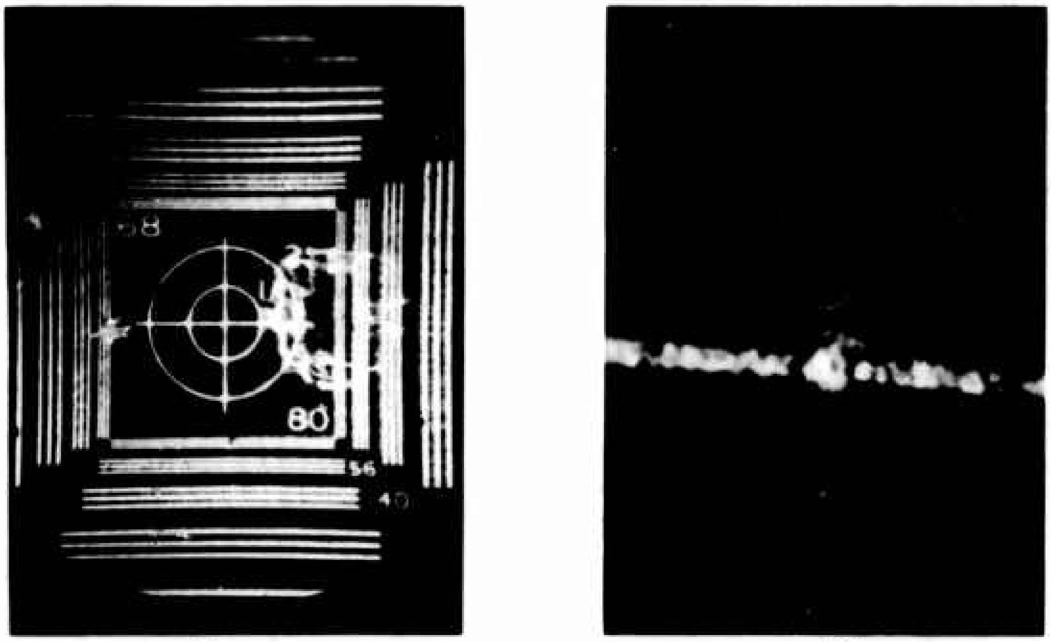


Fig. 1. Quasi-focused image hologram record-reconstruction system.

reference beam at a recording plane to form a stored interference pattern on the recording medium. As discussed in the previous section, a quasi-focused image hologram is formed by moving the recording plane away from the image plane and recording an interference pattern developed between a defocused image and a reference wavefront. Examples of focused image and quasi-focused image holograms are shown in Fig. 2.

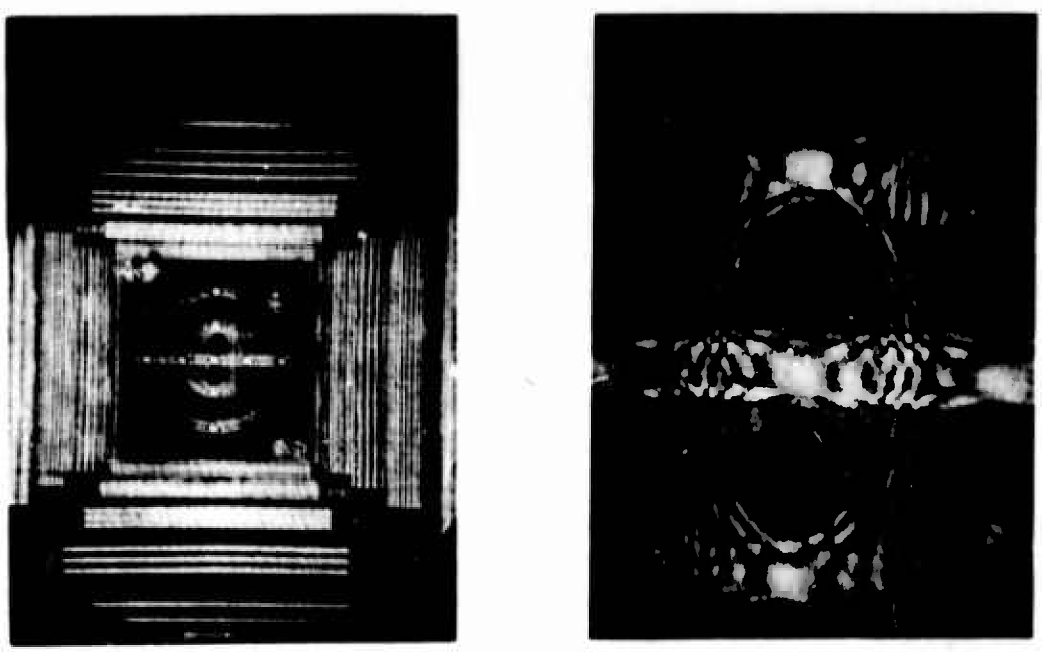
Figure 3 indicates the recording portion of the system. The 4416 Å line of helium-cadmium laser S is used as the coherent optical source. A collimated output signal is gated by a shutter which is employed to control exposure time. The shuttered beam is split into two components by means of beam splitter BS. One component is focused by lens L_1 to a small spot and filtered by pinhole P_1 to eliminate non-uniformities in the wavefront of the beam exiting from the laser. After passing through the pinhole, the beam is allowed to expand to a diameter which is large enough to illuminate the complete transparent object before it is recollimated by large condenser lens L_2. The collimated beam is then transmitted through a transparency containing the information to be recorded (object). A second condensing lens (L_3) is employed to collect the energy transmitted through the transparency and to direct it to an imaging lens.

An imaging lens L_4 is placed at the focal plane of L_3. This lens forms a real image of the object in space. For the focused image case, a holographic recording plate H is placed in the image plane of this lens. Mirror M_4 is included in the diagram to allow



(a) (b)

(a) Photomicrograph of a focused image hologram transilluminated with a microscope illumination incident from the reference beam angle. The magnification is 20x. This hologram would be read out by the display system at a magnification of 15x. The spatial frequency marked 80 on the chart would be read out as approximately 9 cycles/mm on the projection screen. This is not a system limit, however, but arises from the size of the available test chart and the microscope setup, (b) Same as (a) except magnification is increased to show fringes.



(c) (d)

(c) Photomicrograph of quasi-focused image hologram taken under same conditions as (a). (d) Same as (c) except magnification is increased to show fringes.

Fig. 2. Photomicrographs of focused image and quasi-focused image holograms.

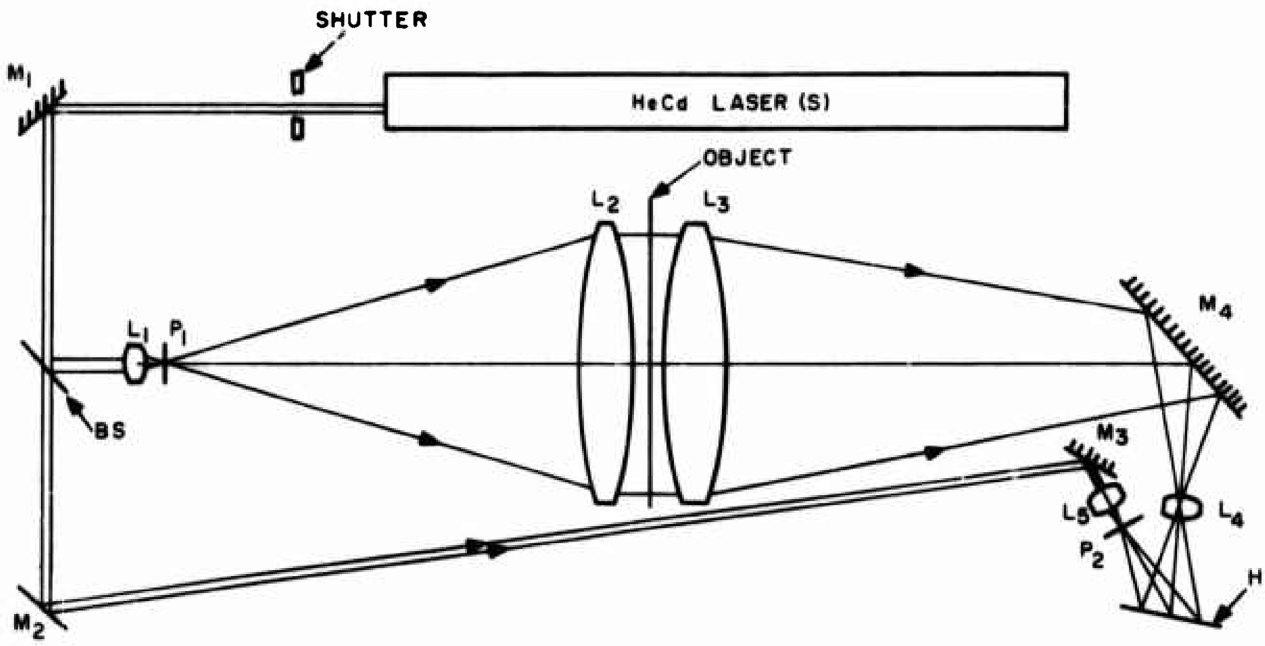


Fig. 3. Quasi-focused image construction.

the imaging optics to be folded so that the setup can be established on an existing stable table. In the quasi-focused image system, the holographic plane is established by moving the recording plate toward the imaging lens.

The reference wave is derived from the same laser; it is formed from the beam which is transmitted through the beam splitter. This component is routed by mirrors M_2 and M_3 to lens L_5 which focuses the beam to a small point. As before, a pinhole (P_2) is employed to eliminate nonuniformities in the wavefront. The energy passing through the pinhole emerges as a spherical wavefront and in this form interferes with the object beam at the hologram recording plane.

Reconstruction may be accomplished using the same coherent source as was used to record the image or a filtered white-light source. Figure 4 indicates the setup for reconstruction using a coherent source in the transmission and reflection modes. Major emphasis was placed on reconstruction in the reflection mode. Reconstruction in the transmission mode was used for system setup and for material evaluation experiments.

Reconstruction in the reflection mode is accomplished by directing the reconstruction beam along the same path and through the same optics that were used to derive the reference beam during construction of the hologram. The beam strikes the hologram and is reflected. A large portion of the energy is reflected in the

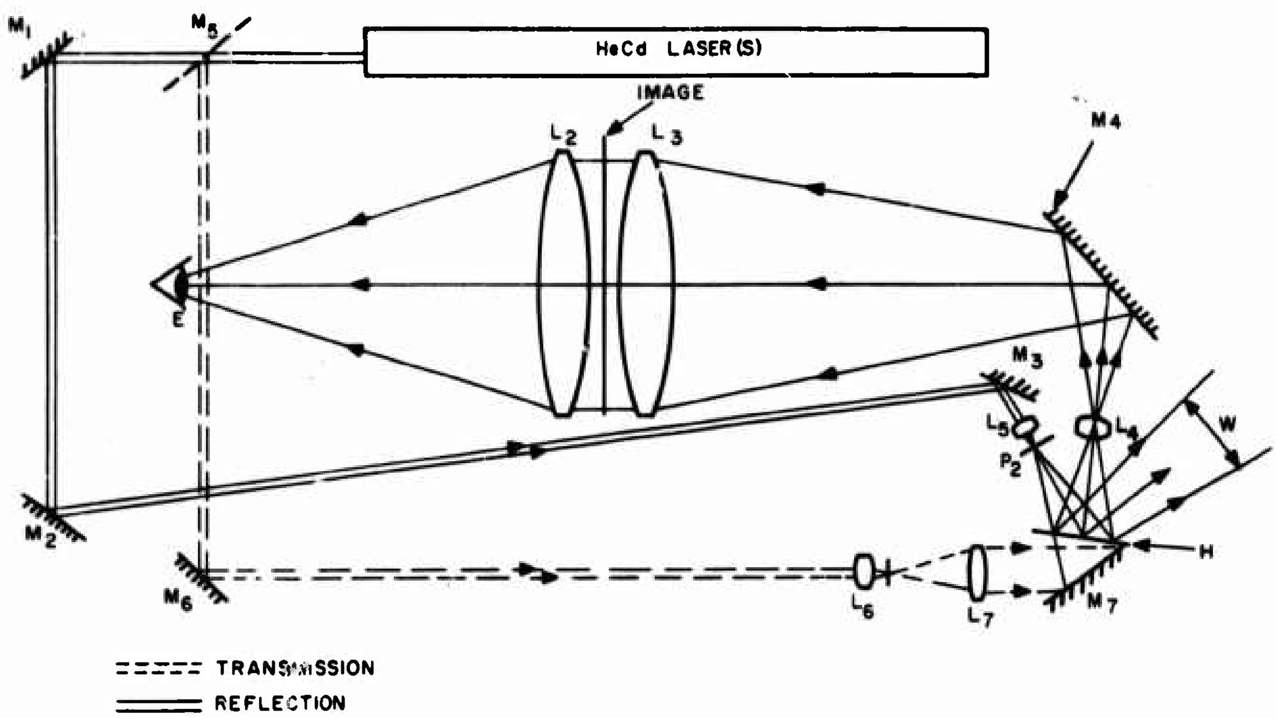


Fig. 4. Coherent source reconstruction.

first-order cone W; a portion of the energy, however, is refracted into an image-forming wavefront which is collected by lens L_4 (a lens having the same aberrations as the original recording lens). This energy is reflected back along the original object beam path to form a real image on a diffuse screen placed at the original object plane, or a virtual image as viewed by an eye at position E.

Reconstruction in the transmission mode is accomplished using an optical system employing mirror M_5 and lenses L_6 and L_7. The lens system is utilized to form a wavefront which travels through the medium to form a point image at point P_2, or at the position where the pinhole used to filter the construction reference beam had been located. Used in this mode, the energy refracted towards lens L_4 is collected by L_4 and directed along the path of the original object beam to form a real image at the original object plane or a virtual image at eye position E.

A full-color image is recorded using as objects three color separations. Three separate holograms corresponding to each of the three color separations are made on the same area of the recording medium, but with the reference beam impinging on the storage material at a different angle for each recording. In the laboratory system assembled for this program the reference beam is held fixed. The variation in the recording angles is acquired by rotating both the storage medium and (by a corresponding amount) the axis of the object color separations. The rotation is introduced

in a plane perpendicular to the optical axis and about the center of the object. Each separation is recorded with the recording plane rotated at 120° from the previous recording.

Three filtered white-light sources are used for reconstruction. The system indicated in Fig. 5 is used for this purpose. In this configuration the three white-light sources are filtered and imaged to form three reference beams (correct gratings are not shown). The reference beams are oriented so that they fall on the hologram at the correct angles to simultaneously reconstruct the color images in the same image space to form a full-color image.

C. ACHROMATIC HOLOGRAPHIC RESTORATION

As indicated in Section III B, color restoration is obtained by storing three separate interferograms (holograms) on the same frame. Three color-separation negatives are made from the map, and each of these is used in succession as an object for the same hologram. Each is recorded in blue light (0.4416 μm). The ability to separate the colors arises from the fact that a different angle is employed for each color on reconstruction.

On exposure the angle of incidence is the same for each (for example, 15° yields 520 line pairs/mm), but the plane of incidence is changed for each exposure. At playback the red and green reconstruction beams must now be incident at different angles (i.e., the red beam must be incident at about 22°, the green at 18°, and the blue at the original 15°), but the original angles of the planes of incidence are retained.

Narrow bandwidths are required to prevent chromatic smear in the reconstructed image. If three narrowband sources are used for reconstruction, these angles are precisely specified. The narrowband sources could be lasers or well-filtered white lights. White sources producing a continuum across the visible spectrum could be so filtered; but as the filters are narrowed, the ratio of useful light to rejected light becomes unfavorable.

If very broadband filters are used, greater utilization of light results; but, since more than one wavelength is present, more than one direction results for a given reconstructed object point. The hologram grating becomes a wavelength dispersing element and causes reconstructed points to be noncoincident; i. e., a chromatic smear similar to chromatic aberration is evident.

However, this problem can be overcome at least to a first approximation if the reconstruction beam is predispersed by the exact amount to just cancel the effect. This is accomplished by making the broadband light incident on a reflective grating with the same spatial frequency as the dc term of the hologram. The diffracted rays will then

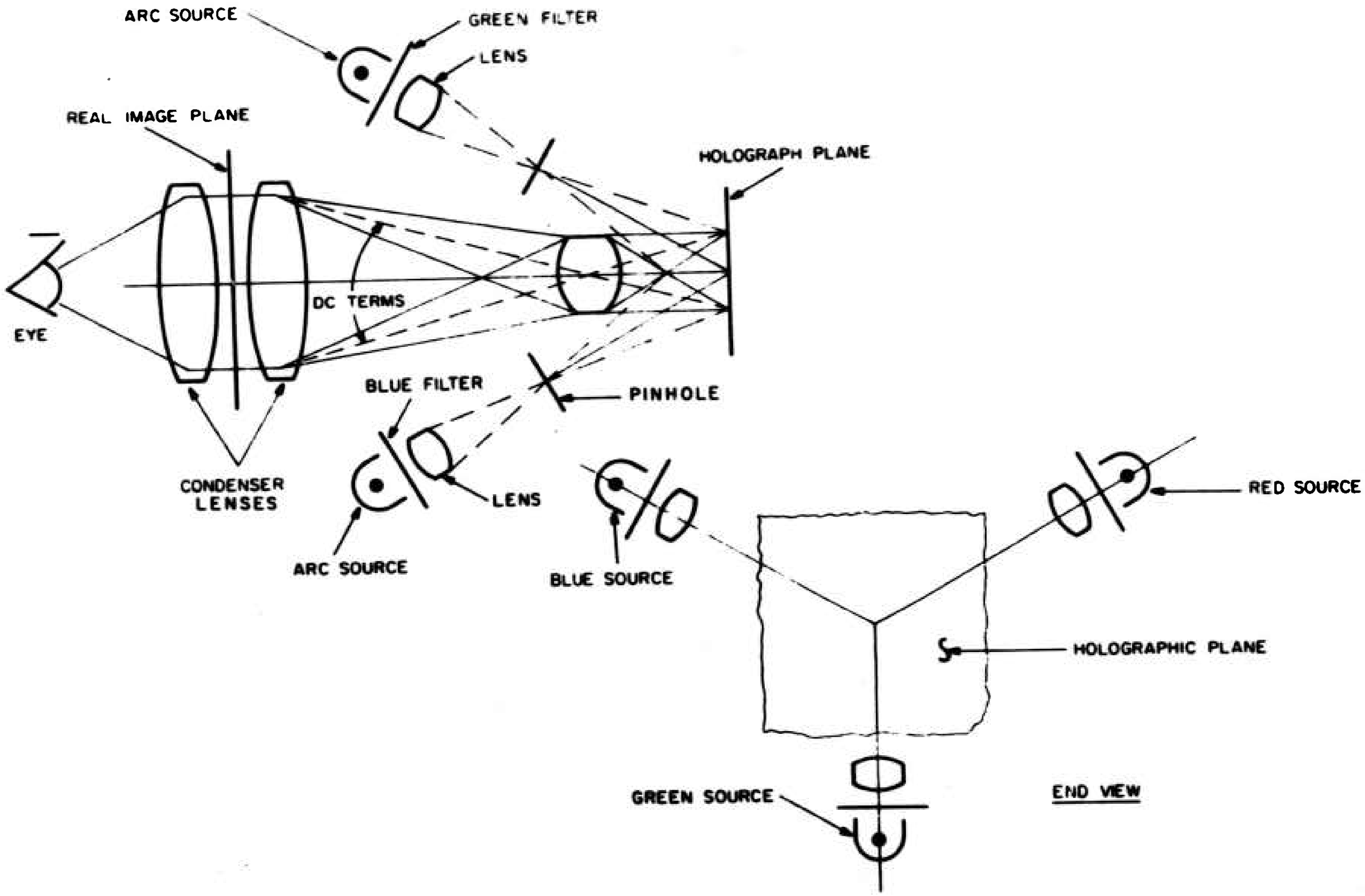


Fig. 5. Three-color restoration.

rays will then leave the grating at angles depending on their wavelength and on spatial frequency. The angular dependence on wavelength is exactly the same for the hologram since the spatial frequency in each case is the same. Thus, the chromatic error is cancelled.

Figure 6 shows the angular requirements for red, blue and green reconstruction paths to produce an on-axis output. Figure 7 shows predispersing grating generation of the angular spread for all reconstruction wavelengths within the broadband interval. Figure 8 shows a method for using this in a practical system. Wavefront processing optics and the blue path are omitted for clarity. The reflection gratings are blazed for first-order peaking in their respective primary wavelengths, producing a 75-percent diffraction efficiency.

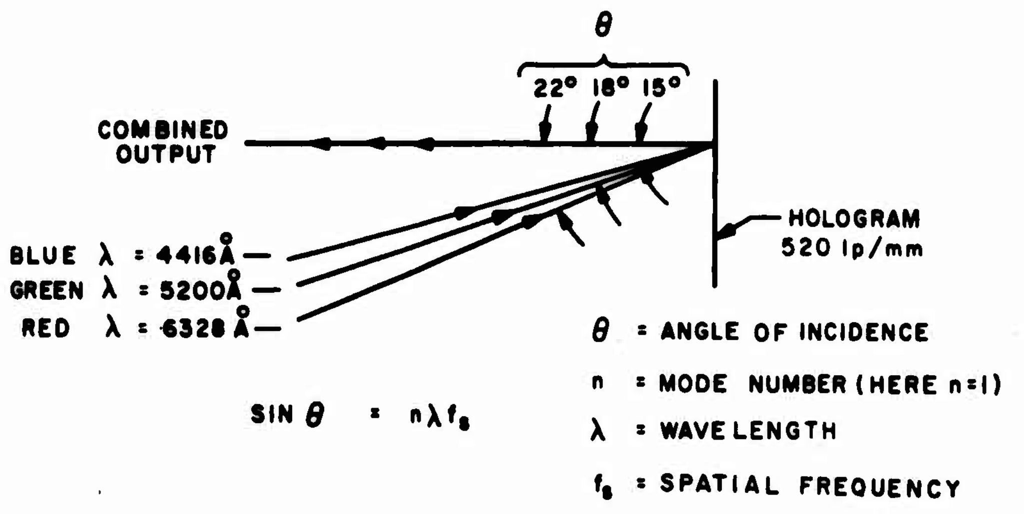


Fig. 6. Reconstruction beam angular requirement.

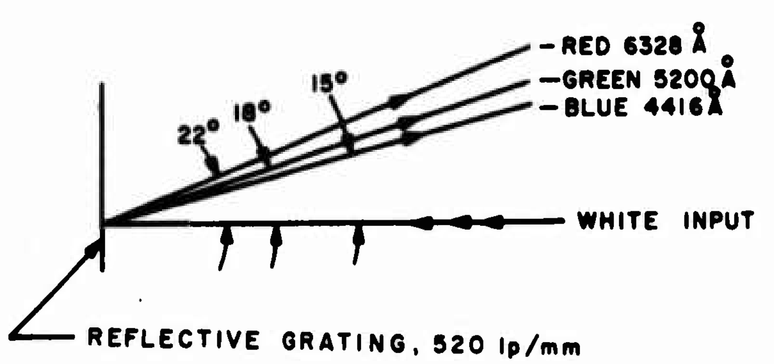


Fig. 7. Predispersion grating.

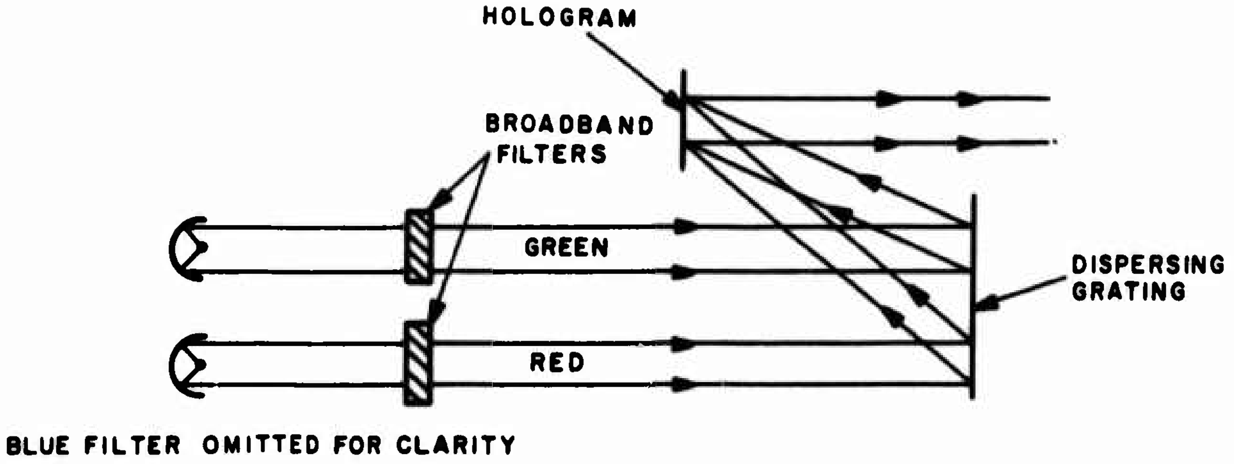


Fig. 8. Achromatic holographic reconstruction system.

Section IV

SYSTEM IMPLEMENTATION

Having once selected the holographic recording form for storing the aerial chart information - the quasi-focused image hologram - a theoretical and experimental analysis was performed to establish the nature and performance characteristics of a holographic multicolor moving map display.

The following areas were investigated under this program.

(1) Redundancy and resolution

(2) Image brightness and contrast

(3) Color Fidelity

(4) Storage Media

(5) Retrival Techniques

(6) Image Motion

(7) Symbology.

These areas are discussed in this section.

A. REDUNDANCY AND RESOLUTION REQUIREMENTS

Redundancy is obtained by recording information elements on a larger area than that necessary for recording these elements as an image. In Fig. 9(a) an object point is recorded in the plane H_1 as a spot of diameter d_s. This is the condition required to produce a focused image hologram. In order for this imaging arrangement to have its maximum resolution, d_s must be as small as possible. In the limit $d_s \approx 1.22 \lambda Z_i/D_A$ where λ is the wavelength, Z_i is the distance from the lens second principal plane to the recording plane H_1, and D_A is the diameter of the perfect lens. In this case both Z_o and $Z_i = 2f$, where f is the focal length of the lens.

In Fig. 9(b) the conditions are the same except the object plane has moved to position O_2 which is in the front focal plane of the lens. $Z_o = f$ and $Z_i = 2f$. Recording in this configuration results in a focused image hologram. This placement allows the dc term to be spread over an area of sufficient size to avoid recording medium saturation. The light from the object point is collimated by the lens and proceeds to H_1 where it is approximately bounded by the diameter D_A.

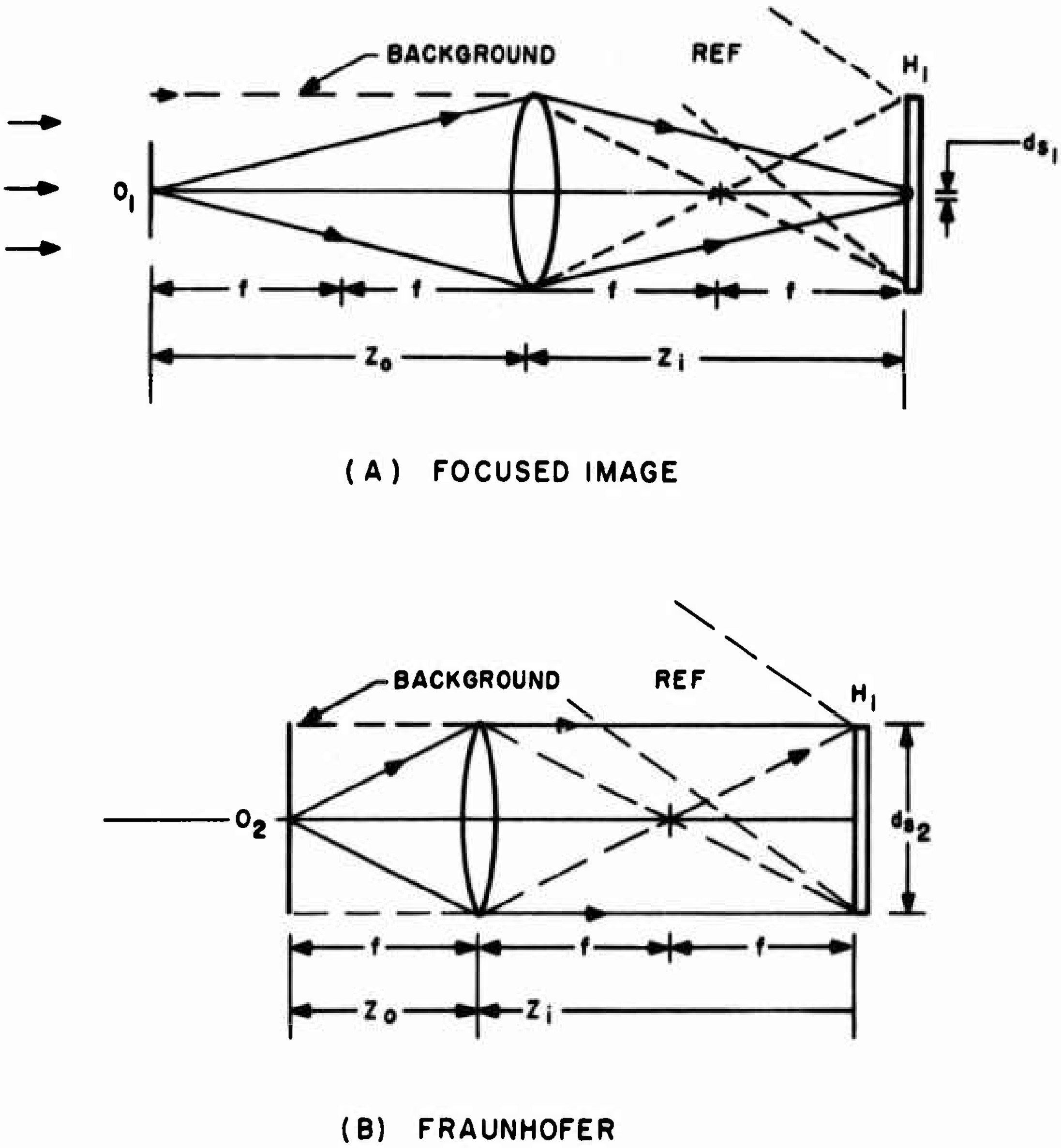


Fig. 9. Two hologram forms.

The area required to image the point in the focused image hologram of Fig. 9(a) is:

$$A_d = \frac{\pi}{4} \frac{\lambda^2 Z^2}{D_A^2}$$ which is the effective Airy disk area.

The Fraunhofer hologram case of Fig. 9(b) yields an area A_H for recording an object point

$$A_H = \frac{\pi}{4} \left(D_A + \frac{\lambda Z}{D_A}\right)^2$$

where A_H is approximately the lens area.

Between these two extreme limits, various values of area can be used to record an image point by varying Z. In practice, one is generally concerned with using as little recording area as possible while maintaining sufficient and only sufficient redundancy to prevent noticeable degradation of the image due to the presence of dirt and scratches and abrasion which occur during normal handling. It must be realized that the penalties one pays for high redundancy is the requirements for (1) greater recording medium area if in all cases the resolution capability of the film is fully utilized and (2) higher coherence of the readout source.

Consider the increased volume requirement. Information in the object can be expressed as a number of bits, this dictates the minimum required recording area. N-fold redundant recording of this set would require at least N times more area than dictated by medium resolution criteria or N times more volume for thick holograms. (Storage medium recording density capability is given in bits/mm^2 for surface holograms and in bits/mm^3 for volume holograms.) For various practical reasons, the information density recorded is often chosen to be less than that of which the medium is capable; therefore redundancy can be added without increasing the required recording area. In this case, however, the bits/mm^2 or bits/mm^3 are increased.

Redundancy is obtained by recording over an excess area but the information is distributed on the recorded area in a complex way. It is a function of the X and Y coordinates and of the spatial frequency making up the object. An example of this is seen by observing the Fraunhofer diffraction pattern of a rectangle. This pattern if observed at back focal plane of the lens resembles a plaid fabric and is the Fourier transform of the rectangle. The intensity distribution is periodic in both X and Y. The higher frequencies caused by the edges of the rectangle are found farthest from the center of the diffraction pattern. If such a recorded pattern is scratched and if the scratch removes a fairly small fraction of the total film area, the resulting reconstruction will not show loss of detail but the diffraction pattern of the scratch will now be superimposed on the readout image. The diffraction pattern will appear as low level noise over a considerable portion of the reconstructed image if only a small portion of the total area is damaged. The same argument applies to dirt and imperfections in the film.

Although redundancy has been added, an undesirable effect is produced in this form; the position of the scratch has an effect on which frequency components are removed and from what area. If, for example, a scratch occurs in the center, low frequency components are removed. A scratch on one side would affect the higher frequencies.

A diffusion screen placed over the object transparency causes the light from every object point to be scattered into paths that cover the lens aperture. This removes the dependence of recording zone position on object spatial frequency, and therefore maximizes the redundancy so that area redundancy and information redundancy are equal. Unfortunately, the random nature of a diffuser gives rise to random frequency components in the recording plane which are observed as beats between the diffuser elements, the object elements, and the reference beam. These beats give rise to speckle in the reconstructed image.

A special diffuser that has ordered rather than random diffracting elements can be fabricated so as to produce multiple object beam illumination. This can be implemented by:

(1) Diffraction grating used between the light source and the object and of such characteristics that it produces nearly the same intensity in zero, first, and second order beams. This grating can be of the two-dimensional phase variety so as to give rise to 25 or more object beams, 9 of which are of equal intensity.

(2) Array of mirrors to produce the same effect

(3) Array of pin holes with or without phase retardation material in the pin holes.

These devices may be called ordered rather than random diffusers and provide most of the benefits of random diffusers but do not produce speckle at readout. They do, however, produce noise. The noise is ordered and is seen as a sampling grating superimposed on the reconstructed image. The sampling frequency can be high enough to be above the resolution required in the readout; and if the readout system is designed to have its cutoff frequency near the multiple object device sampling frequency, the superimposed grating will be filtered out.

A Fraunhofer hologram recorded with n object beams contains n adjacent far-field diffraction patterns of the object, spaced so as to encompass 1/n of the record area. By comparison, a Fraunhofer hologram of the same object recorded on the same sized area using a single object beam and no diffuser would have the same area redundancy. The difference is that a substantial portion of the hologram can be cut out from the multiple-beam recording with the result that the entire object will be reconstructable from the remaining segment. The reconstructed image will have less contrast and lower signal-to-noise depending on the fractional area removed. The single object beam hologram with the same area removed as above will be able to reconstruct a partial image of the object but the portion reconstructed will have higher signal-to-noise ratio and higher contrast than the total image of the comparable multiple-beam hologram.

Redundancy in the holographic system can be designed to provide immunity to scratches or immunity to possible excisions of significant portions of the whole hologram. If the particular application demands the former, the single-object beam offers advantages; if the latter, the multiple-object beam or diffuser is preferred.

Noise is introduced by inhomogeneities in the substrate and emulsion and by imperfections in the surface flatness of both. This noise is much more prominent if coherent light is used to read out the hologram. Since Fraunhofer holograms require coherent readout light, their reconstructed images contain much more noise for a given set of recording film imperfections than would be observed in the reconstructed image from an image plane hologram read out with incoherent light.

If the information of the objects to be recorded is tolerant of minor scratches and dust particles but intolerant of background noise, image plane holograms offer the greatest advantage. If, however, the object content is intolerant of scratches and dirt, but tolerant of background noise, Fraunhofer or Fourier-transform holograms are most desirable. Examples of the former type of object are documents, maps, recce photos, etc., and of the latter, binary data blocks for address codes or numerical information.

In selecting which type of hologram is most suitable for a given application, the above mentioned variables must be considered and, in general, a recording system should be designed to provide only as much redundancy as required.

The redundancy required in this case is arrived at by consideration of the resolution needed, the maximum size of the scratch or dust particle, and the allowable degradation in the reconstructed image.

The remarkable scratch immunity of polyvinyl chloride (See Section IV D) used in this application reduces the redundancy requirements of the map records to a value based on the scratch sizes expected after a thousand hours of tape travel. From limited laboratory tests, we estimate that the scratches appearing after moderate usage are in the order of a few microns in width if the tape has not been allowed to become unduly dirty. A well-designed cassette protects the tape adequately against dirt.

If the observed screen resolution limit is 10 line pairs/mm, and a system is constructed which has a 15:1 linear reduction from display size to storage size, the diameter of a hologram resolution element area is 0.0067 mm. Any area in excess of this $[A_R = \pi (7 \times 10^{-3})^2/4 = 3.54 \times 10^{-5}\ mm^2]$ is useful in giving the spot a measure of immunity from obliteration. Scratches observed on vinyl tape holograms that had been used for demonstrations under field conditions with no protective cassette appear to be distributed in size from a fraction of a micrometer to about 9 μm. The predominant scratch size ranges from 3 to 6 μm.

In selecting an appropriate area factor for recording the 6.7-μm-diameter resolution element, it is of importance to consider the effects of two tradeoff parameters on the overall system:

(1) The more redundancy designed in, the smaller the readout beam bandwidth. This causes the reconstruction light source to be effectively less efficient since band-limiting an incandescent source reduces light available from it for a given power input, or requires a coherent source such as a laser which has undesirably low efficiency as well as larger size and weight.

(2) The high efficiency system is more dependent on the characteristics of the material used for recording and on the measures taken to prevent dirt and scratches. A well-designed cassette, a means for preventing static electric charge buildup on the tape, and a transport system designed for cleanliness in operation are of paramount importance.

Effective solutions to these problems do not necessarily involve large or massive power consuming devices.

If the condition is imposed that no object resolution element shall be lost by a scratch of up to 90% of the maximum size scratch expected in reasonable service, i.e., 9 μm wide and many times as long, then contrast degradation in a scratched area is 1/n and the area used to record a resolution element should be n times that of the scratch bounded by the diameter of the circular record area:

$$\frac{\pi D^2}{4} = nDS$$

where S is the scratch width, D is the diameter of the circular area used to record the resolution element, and n is the redundancy as seen in Fig. 10.

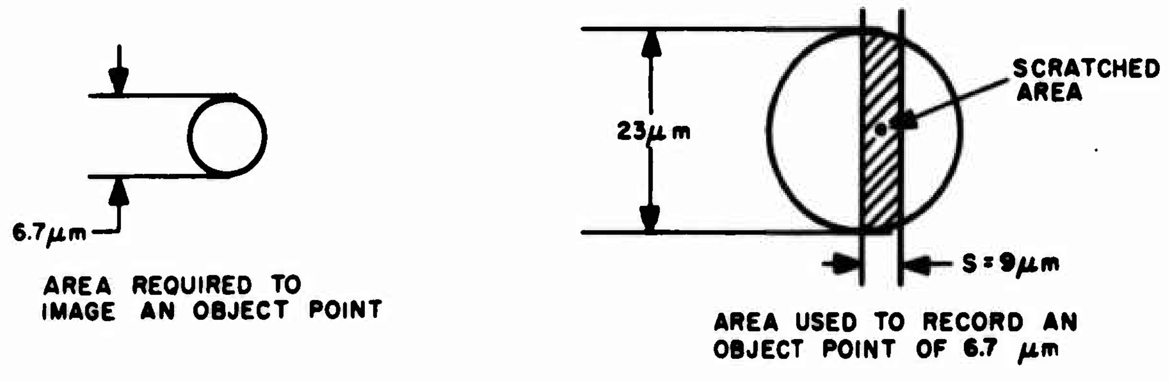


Fig. 10. Redundancy effect.

$$D = \frac{4nS}{\pi}$$

The scratched area is approximately DS. This approximation neglects the difference in area between a rectangle and the area of the inscribed segment of the circle. This difference is small when $S \leq D$, a condition that exists when $n \geq 1$.

For two-fold redundancy, the recorded spot diameter, $D \approx 8S/\pi \approx 23\ \mu m$ and the contrast loss for the scratched portion will be 50%, a very reasonable value for a practical display.

B. IMAGE BRIGHTNESS AND CONTRAST

1. Contrast

In order for a projection map display to be useful in a high ambient light environment, the observed contrast should be approximately as high as that on the reflected map from which the hologram was made. Projection systems of all kinds tend to degrade contrast, especially in high ambient light.

For the purposes of this discussion, the contrast C is defined as

$$C = \frac{I_1 + I_3}{I_2 + I_3} \tag{1}$$

where I_1 is the transmitted highlight brightness of a spot on black background, I_2 is the transmitted brightness of the background, and I_3 is the projection screen brightness of a black area caused by reflected ambient light.

In order to deliver an image contrast equal to that of the map, the image must have a higher contrast than the map by an amount determined by the contrast degradation in the system.

The dynamic range capability of the hologram's reconstructed image can greatly exceed that of the map and is therefore not a limiting factor. The maps themselves are estimated to have a range of approximately 10:1 from the white areas to the "black" ink areas. (The apparent map contrast depends on the illumination quality, the illumination angle, and the condition of the map.)

Two factors of prime importance in determining the necessary projection screen illuminance to achieve a given image contrast are (1) screen reflectivity, and (2) ambient illumination.

The term I_3 in the contrast equation, eq (1), represents the brightness of a black area. If $I_3 = 0$, the screen contrast is the same as the projected image contrast and the system input light can be minimum.

In any physically realizable system, however, I_3 cannot be zero because the screen reflectivity cannot be zero. The reflectivity can, however, be made quite low if special techniques are used. For example, a good rear projection screen such as Polacoat LS 75 is directional and appears to be dark gray. It's reflectivity is given as 0.11 and is representative of a variety of such screens on the market. This screen is only 57% to 65% transmissive but does have a gain of 5 over a lambertian diffuse screen.

Any projection screen will degrade the contrast of the projected image if the ambient light is greater than zero. The extent of this degradation is determined from eq (1) as follows:

$$C_{Ps} = \frac{I_1 + I_A R_s}{\frac{I_1}{C_i} + I_A R_s} \tag{2}$$

where

C_{Ps} = contrast of image as displayed on projection screen

I_1 = projected image highlight brightness

I_2 = I_1/C_i

C_i = contrast of projected image

I_3 = $I_A R_s$

I_A = ambient illumination

R_s = projection screen reflectivity

Expressing I_1 as a fraction of ambient illumination ($I_1 = K\, I_A$) and substituting in eq (2)

$$C_{Ps} = \frac{K\, I_A + I_A\, R_s}{\frac{K\, I_A}{C_i} + I_A\, R_s} = \frac{K + R_s}{\frac{K}{C_i} + R_s} \tag{3}$$

Figure 11 is a plot of eq (3); it shows the screen contrast as a function of screen reflectivity for various values of K. This is done for an image contrast of 20. The map contrast is approximately 10 but this can be recorded as a hologram with a contrast greater than that of the map. A value of 20 was chosen here as a practical value obtainable with our system. Larger values are attainable but the benefit is negligible since contrast fall-off is very rapid for practical values of K. It is clear from Fig. 11 that the contrast degradation produced from commercially available rear projection screens is intolerable unless the input to the screen is more than twice as bright as the ambient, i. e., $K \geq 2$. Such projected image brightness in the cockpit environment where thousand of lumen/ft^2 are incident on the viewing screen would require enormous input power resulting in undesirable weight, size and power consumption.

Therefore, a directional rear projection screen having a reflectivity of approximately 0.75% was designed. With this screen no overall contrast degradation would occur in ambients as high as 300 footcandles and with an input image highlight brightness of about 75 footlamberts. A detailed description of this screen will be given later in this section.

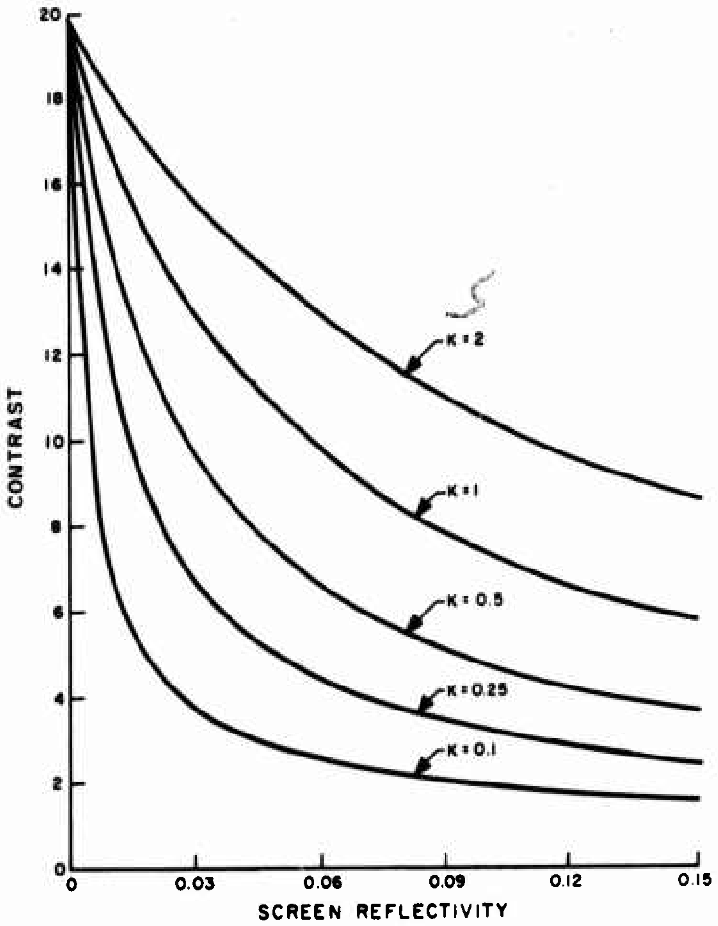


Fig. 11. Screen contrast as a function of screen reflectivity for various K values.

The highlight brightness obtained from the hologram depends on (1) the efficiency of the hologram, (2) the effective brightness of the optical sources, and (3) the optical efficiency of the projection system. The light sources now in use (three 150W xenon arc lamps) each produce 3000 lumens, radiated into 4π steradians. The feasibility of using tungsten sources has also been investigated. The tradeoff which defines which source is used depends on the degree of redundancy required which in turn relates to the size of the source which can be tolerated. In either case this analysis assumes the xenon point sources.

If a lens having an aperture of 14.2 mm diameter and a focal length of 28.6 mm* is used to collect and collimate the light, the solid angle Ω subtended by this lens is

$$\Omega = 2\pi \ (1 - \cos \theta)$$

where θ is the half cone angle = 14°. Since cos 14° = 0.970

$$\Omega = (6.28) \ (1-0.97) = 0.1884 \text{ steradian}$$

Therefore the usable light collected by the condenser is

$$3000 \text{ lumens x } \frac{0.1884}{4\pi} = 47 \text{ lumens}$$

This light is not all collected by the hologram since the hologram diameter is 10 mm. The effective lens aperture is, then, 10 mm but the 14.2 mm is used to provide an alignment margin. The effective light collected is

$$\frac{(10 \text{ mm})^2}{(14.2 \text{ mm})^2} \text{ x } 47 \text{ lumens} \approx 23 \text{ lumens}$$

This will be incident on a plane defined by the 6-in by 2.34-in eye relief area. This area is 0.1 ft^2.

So that $I = \dfrac{23 \text{ lumens}}{0.1 \text{ ft}^2} = 230 \text{ lumens/ft}^2$

*The lens focal length should be minimal since the numerical aperture is inversely proportional to focal length for a given aperture. However, the focal length must be great enough to achieve the required collimation. The required collimation angle is dependent on the bandwidth and the spatial frequency of the pre dispersing grating. An angle of 2 degrees is appropriate and this angle is obtained from a 1-mm-diameter arc source if the focal length is 28.6 mm.

This value of I multiplied by the optical efficiency of the system gives the value I_1 to be used in eq (2) and is the value for a white light continuum source.

Since the system here uses three color primaries to obtain white, and since the bandwidth for each primary is smaller than one-third of the visual spectrum, the sum of the primary component intensities will be less than the above value for I_1. For example, if the bandwidth of each primary is one-sixth of the visual spectrum, the sum of the three primaries derived from the 3000-lumen sources described above would be:

$$\frac{I_{1r}}{6} + \frac{I_{1g}}{6} + \frac{I_{1b}}{6} = I_1$$

and if the peak values of I_{1r}, I_{1g} and I_{1b} are equal to 230 lumens, then

$$I_1 = 115 \text{ lumens/ft}^2$$

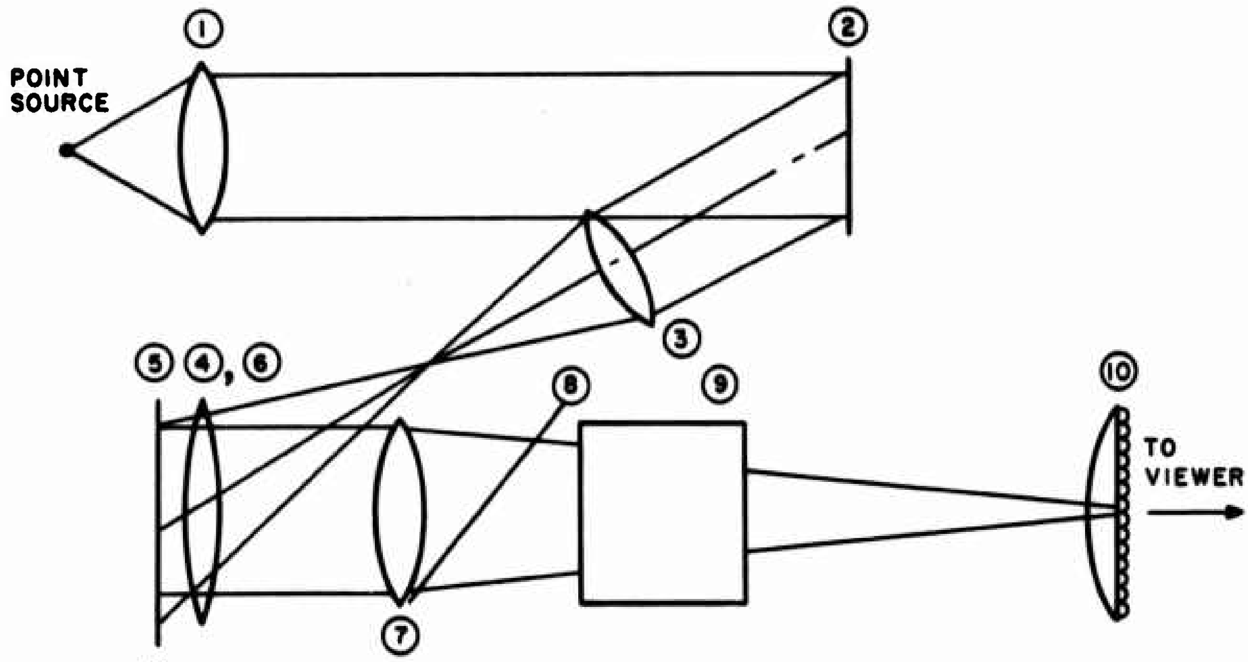
This lower screen illuminance caused by restricting the primary color bandwidth results in a large color saturation capability; however, the printing inks used in map making are not highly saturated. Color saturation can be traded for brightness by increasing the bandwidth. For example, if the color primary bandwidth is made 0.33 of the visual spectrum, and three sources are used, the output brightness will not be reduced over a single source black and white system. The evaluation performed under this study (see Section IV C) indicates that acceptable color rendition is acquired if the primary bandwidths are approximately 0.25 the visible spectrum resulting in $I_1 = 173$ lumens/ft^2.

For a given input brightness in color or black and white, the projection screen is of critical importance.

2. Optical System Efficiency

Figure 12 indicates the configuration of the viewing system used for the map display. All components which tend to degrade the optical efficient are indicated in the diagram with transmission (or efficiency) values. A single source is shown having a spectral bandwidth of 0.75 of the visible spectrum. The source produces a flux density I_s in the viewing area

$$I_s = I_1 \eta_{sys}$$



ELEMENT	NAME	OPTICAL TRANSMISSION EFFICIENCY *
1	COLLECTION LENS	0.98
2	PREDISPERSION GRATING	0.98
3	REFERENCE BEAM FORMING LENS	0.98
4	RECTIFICATION LENS	0.98
5	MULTI-EXPOSURE HOLOGRAM (HIGHLIGHT)	0.09
6	RECTIFICATION LENS	0.98
7	IMAGING LENS	0.96
8	CHARACTER INSERTION PELLICLE	0.90
9	ROTATING PRISM (PECHAN)	0.87
10	CONDENSER LENS - LENTICULAR SCREEN	0.86
11	SYSTEM	0.057

* ASSUMES ANTIREFLECTIVE COATING THROUGHOUT

Fig. 12. Viewing system configuration schematic.

where I_1 = the unattenuated screen brightness derived above and η_{sys} = the system optical efficiency.

For I = 173 lumens/ft^2 as derived above and η_{sys} = 0.057 from Fig. 12, the illumination in the viewing area is 9.85 lumens/ft^2 as viewed by an observer 30 inches from the viewing screen with an eye relief area of 2 in x 6 in.

This illumination level is equivalent to that which would be produced in the eye relief area by a diffuse (lambertian) surface with a brightness of 985 footlamberts, assuming the surface is 6 inches in diameter and the viewing distance is 30 inches.

3. Projection Screen

The image from the hologram can be made incident on a diffusing screen in order to accommodate a large eye relief area. There are two disadvantages: (1) The diffuse reflectivity of available screens is high (10% to 30%) and therefore considerable ambient light is reflected into the observer's eyes which diminishes screen contrast, and (2) the projected image light is spread over a larger area than necessary and consequently provides a less bright image.

An ideal projection screen would exactly fill the eye relief area as defined by the observer requirements so as to conserve input power to the system. The reflectivity would also be very low in order to prevent contrast degradation.

Each element of the projected image must be spread so as to fill exactly the eye relief area. This can be done with a screen comprised of a transparent substrate supporting a multiplicity of small lenses. Each lenticule may not be larger than a resolution element. If the eye relief area is circular, the lenses may be spherical; but if the defined area is rectangular, the individual lenses must have a cylindrical component.

The eye relief area chosen for this display is 6 in wide by 2.34 in high. This allows an observer with an interpupilary distance of 2.5 in to move his head from side to side about 3.25 in (total travel) and up and down approximately 2.25 in (total travel) and see all the image with both eyes. (He may move his head almost 6 in from side to side and still see the image but at the extremes one eye rather than both eyes is capable of viewing the image.)

A lenticule diameter of 0.1 mm would limit the resolution to approximately 10 line pairs/mm. The focal length of the lenticules would be determined by the distance of the observer to the screen (30 in) and by the dimensions of the eye relief area.

The viewing geometry is shown in Fig. 13. The figure shows the composite screen in which the lenticular elements have a higher power in the horizontal meridian.

The focal lengths of the lenticules in the horizontal and verticle planes are different to accommodate the rectangular shape of the eye relief area.

Screens with these specifications can be pressed from glass using master dies. The glass can then be antireflection coated. Since unpolarized light is used in reconstruction, the glass may be heat-treated to make it "safety glass". The screens could also be made from plastic at less expense but they would not be as durable nor would the antireflection coating perform as well.

At present, we have found no lenticular screens on the market that have the exact specifications listed above. But in order to demonstrate the feasibility of this approach, we have obtained a screen having almost the correct focal length; and although its spatial period is too great to preserve the required resolution, it does serve the purpose of demonstrating increased contrast and brightness over conventional screens. Dies would be required to obtain screens to our specifications. Once the dies are made, the cost per screen would be quite low.

4. Contrast

In order to define the system contrast as viewed from the eye relief area, it is necessary to determine the flux density in that area resulting from energy reflected

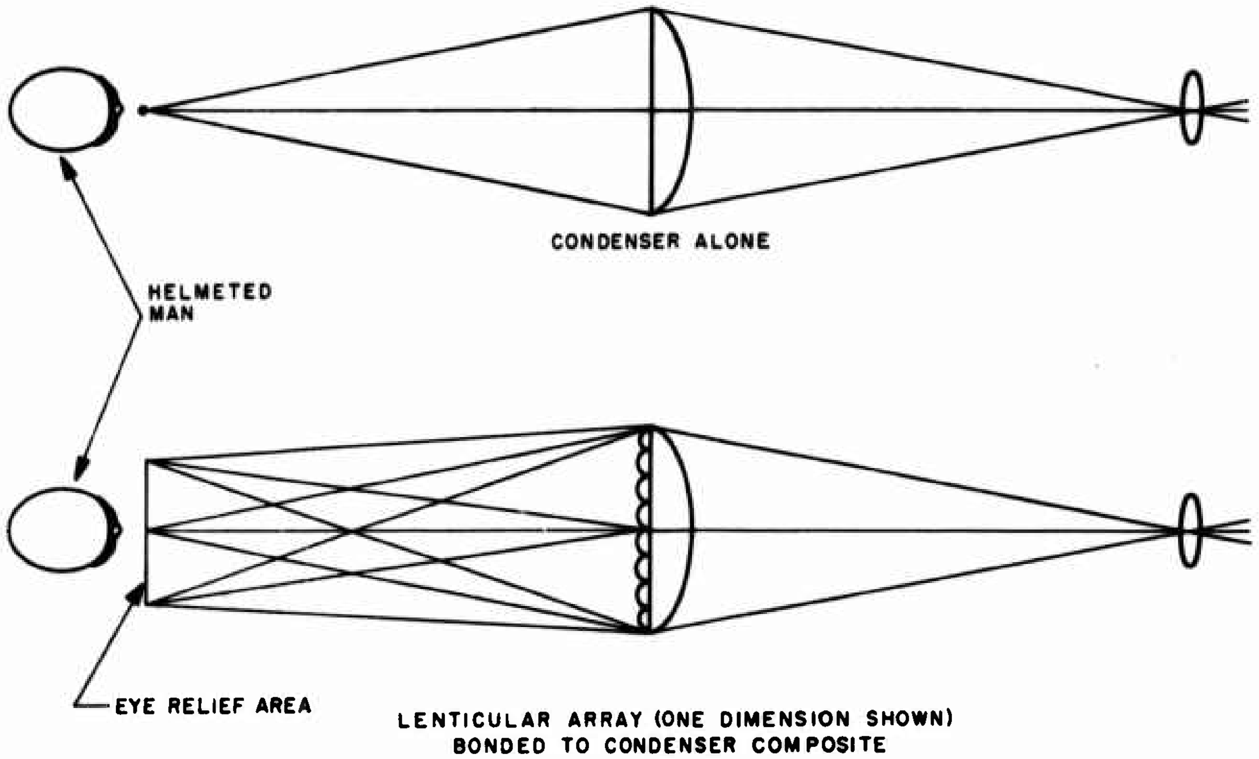


Fig. 13. Viewing geometry.

or scattered from the viewing screen. This is the I_3 term of eq (1), in which the contrast is defined as

$$C = \frac{I_1 + I_3}{I_2 + I_3}$$

where

I_1 = high light intensity

I_2 = low light intensity

I_3 = ambient intensity.

In order to specify I_3 consider Fig. 14 which is an exploded view of the viewing screen of Fig. 12. The lenticular screen and condenser lens are composed of material of the same index of refraction and are cemented together so that reflections from ambient illumination incident on the screen from the viewing side are only acquired from surfaces A and C. Both these surfaces are coated with an efficient antireflective coating. For the purpose of this analysis, it is assumed that the reflection coefficient of the lenticular surface is of the order of 0.5%, and that of the rear surface is 0.25%.

Consider first the front surface lenticular array which has a reflection coefficient, ρ_f, of 0.5%, causing 0.5% of the ambient illumination falling on the screen to be reflected. A fraction of this energy will be reflected back into the viewing area (the 2.34 x 6.00-in eye relief area). This occurs due to the fact that each lenticule, which for the map information acts as a small lens having a different power in the X and Y direction, acts upon the reflected ambient illumination as a convex reflector

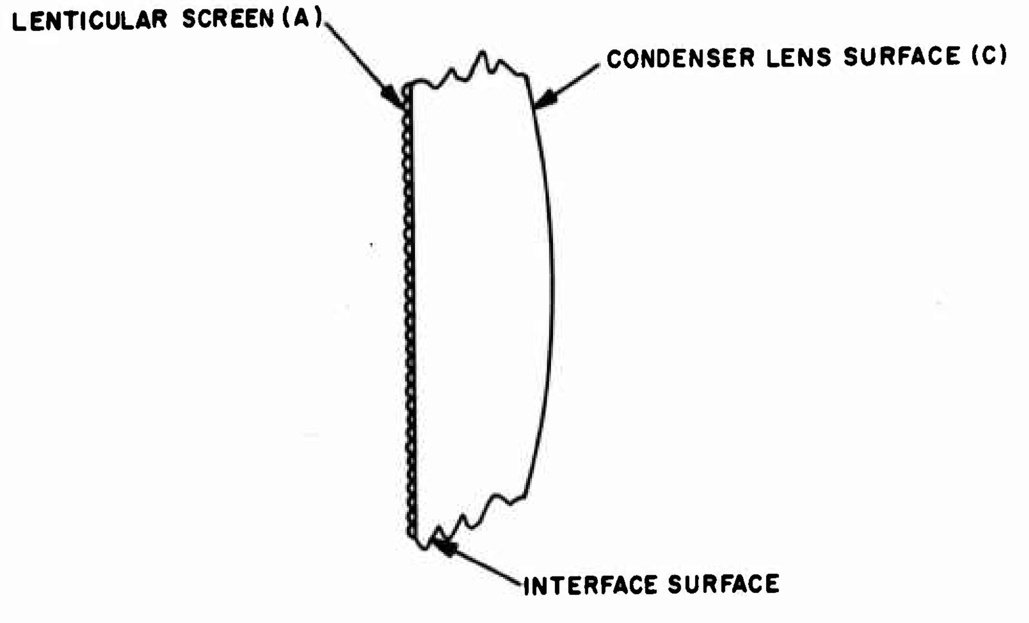


Fig. 14. Viewing screen, exploded view.

with different powers in X and Y. Consequently, illumination from a point source falling on an individual lenticule appears to an observer to be coming from a vertical image of the point located behind the reflecting surface. The energy reflected into the eye relief area is only reflected from that portion of the lenticule included within the solid angle defined by the lines connecting the point source and the extremes of the viewing area. Since the lenticules are small with respect to the viewing area, the observer views a general reduction in the illumination level over that which would be produced by a spectrally reflecting surface reflecting all the energy incident upon it into the viewing area. Although the discussion is concerned with a point source, any object can be considered as a collection of point sources resulting in a similar attenuation of the reflected energy.

Consider the lenticular array proposed for this application. Each lenticule has a radius of curvature in X and Y determined by the lens power required to fill the eye relief area with the map information projected through the viewing screen. The geometry of this lens in the transmission and reflection modes is shown in Fig. 15 and 16, respectively. For the dimensions shown, each lenticule has a radius of curvature of 0.25 mm and 0.546 mm in the X and Y directions, respectively. For a point source located on the optical axis at a distance from the mirror (a distance large with respect to the radius of curvature of the mirror), light is reflected into the viewing area from a point which appears to the observer to be located midway between the reflecting surface, S, and the center of curvature of the mirror, O. The intersection of the cone ABDCO and the reflecting surface, S, defines that portion of the lenticular surface which reflects energy into the eye relief area. The ratio of this area to the

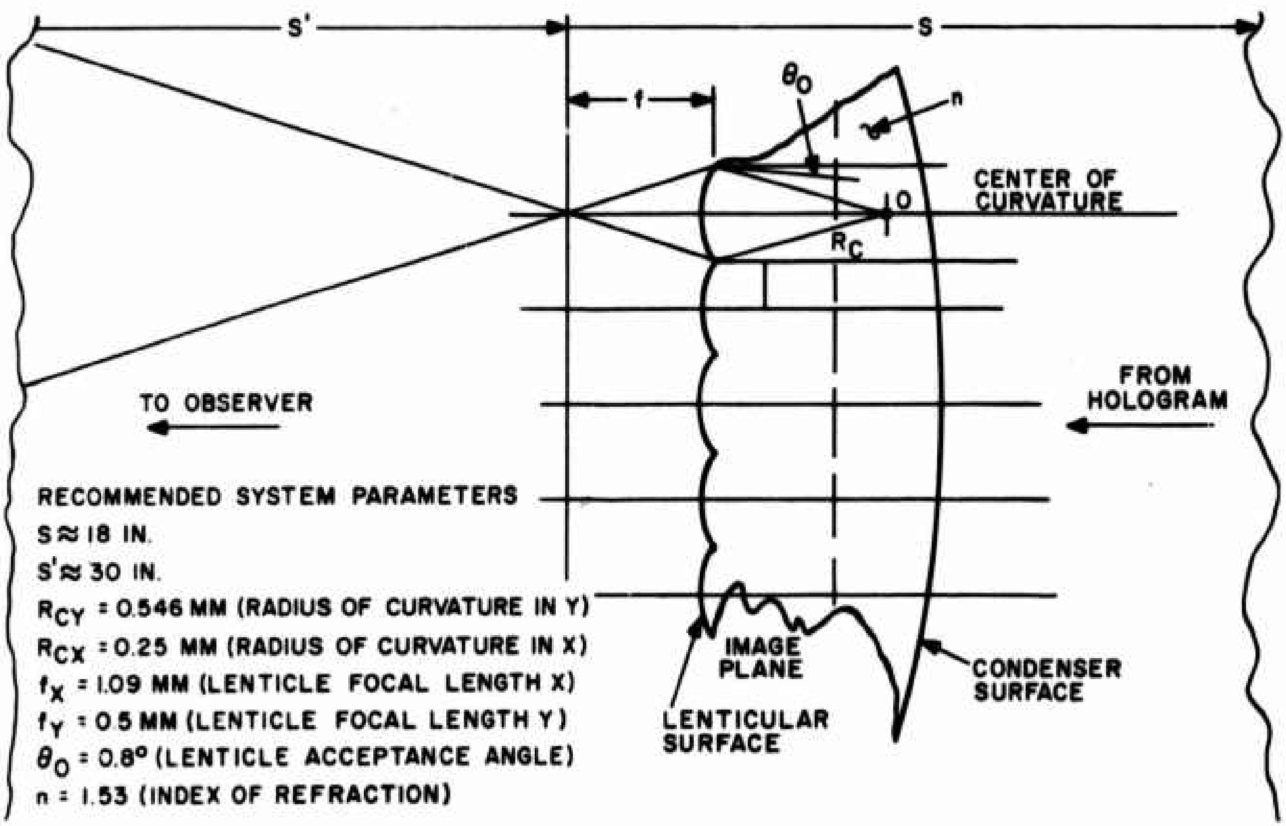
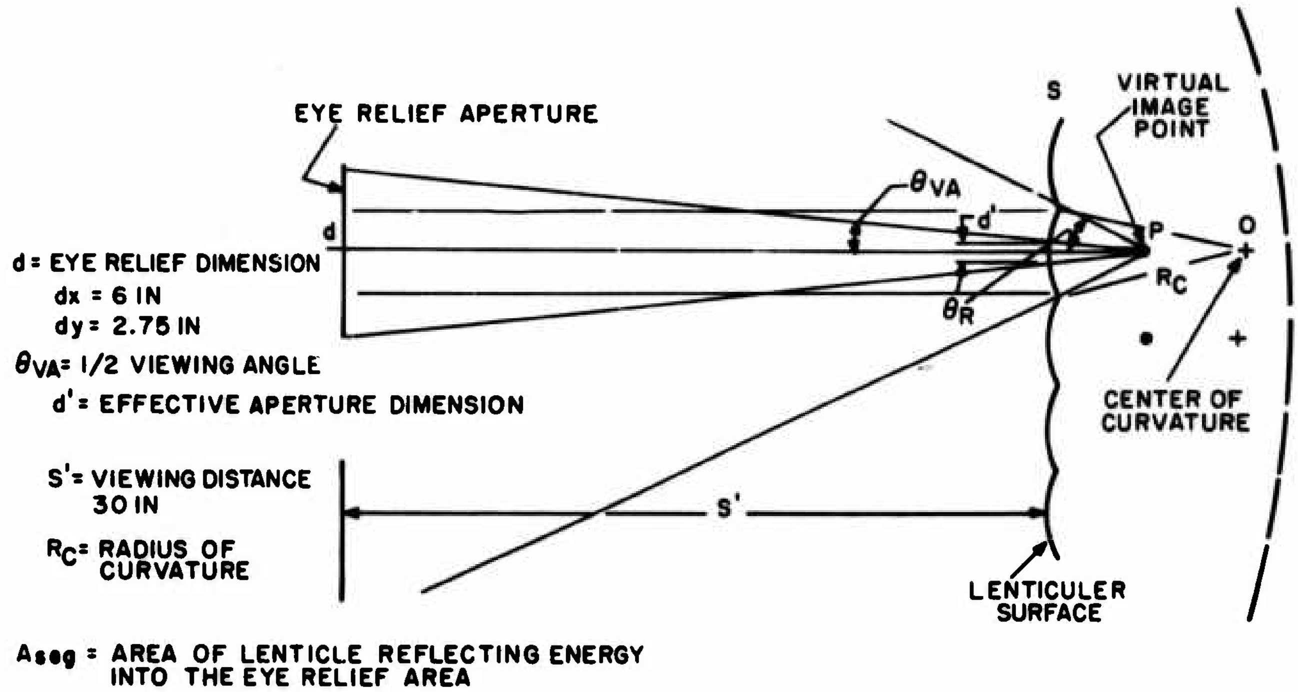


Fig. 15. Viewing screen ray trace - transmission.



$$= 4 R_{cx} \left(\frac{R_{cx} d}{2S' + R_{cx}}\right) \tan^{-1}\left(\frac{d}{2S' + R_{cy}}\right)$$

Fig. 16. Viewing screen ray trace - reflection.

area of the lenticule defines a further attenuation factor for the reflected illumination. For the geometry of the screen shown, the attenuation factor, η_f, is 0.22 as derived in the development of Fig. 16.

The back surface of the lenticule-condenser lens combination is a concave surface. For the geometry of the display described in Section III, energy striking the back surface is reflected back toward the eye relief area. If the optical energy is coming from a distant point on the optical axis it is focused to a point approximately 20 in. in front of the eye relief plane. The energy eminating from the 6-in-diameter circular viewing screen area will consequently fill a 12-in-diameter area in the plane of the eye relief area to produce a flux density equal to 1/4 the flux density incident on the screen or a collection efficiency η_b = 0.25. The surface is uniform and can be coated so that its reflection coefficient, ρ_b, is of the order of 0.25%.

Consequently, the illumination reflected back into the viewing area becomes

$$I_R = I_A (\eta_f \rho_f + \eta_b \rho_b) \text{ lumen/sq. ft.}$$

Assuming the worst incident ambient energy to be 1 x 10^4 lumens/sq. ft. (the display is shielded so that it is not in direct sunlight, but a high sky condition exists) the ambient illumination reflected into the viewing area from the viewing screen becomes

$$I_R = 10^4 \ (0.005 \times 0.22 + 0.0025 \times 0.25) = 3.4 \text{ lumens/sq. ft.}$$

Assuming a high light level of 9.85 lumens/sq. ft. for the map information as derived previously, a contrast, C of approximately 3.9 is developed (assuming a high map contrast).

In order to acquire contrast of the order of 10:1, the display must be positioned or hooded so that the reflected illumination, I_R, is of the order of one lumen/sq. ft., or the hologram brightness must be increased. The display brightness may be increased by using a focused image hologram eliminating the predispersion grating and using optical power sources of higher intensity. If this is done, three 500-W sources without the dispersion grating will allow the development of a hologram having highlight brightness approximately three times that indicated above resulting in a 10:1 contrast.

RCA recommends that the hood and the quasi-focused image hologram with scratch immunity capability be employed; using this approach only light coming directly from the viewing area will be incident on the viewing screen. The display would in this case be obscured to the degree that it could not be easily read (i.e., below a contrast of 10:1) only if a spectral reflection was directed directly toward the display from the viewing screen. An example of this condition would be produced by sun glint off the pilot's visor.

C. COLOR FIDELITY

Color separation transparencies of the map are used as objects in forming the multiple-exposure, focused-image hologram recording. The color primaries selected for producing these color separations differ from those used in printing. Colored inks available today are of such composition that in order to reproduce the specified range of colors in a military chart, four or more inks must be used. Often in high-quality work more than nine separate inks are needed. Reproduction in the holographic display is accomplished using only three primaries.

Three-color separations made by photographing the chart through each of three filters allow sufficient capability for reproduction of all printing ink colors.* The filters are chosen so that their trichromatic coefficient coordinates form a triangle that encloses the coordinates of the various inks. The filter coordinates obtained with Kodak Wratten filters 58, 47B and 25 is shown in Fig. 17.

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*According to D. McAdam of Eastman Kodak the limits of the best inks available today are given by the area shown in Fig. 17.

The film densities arising from the use of these filters is a function of the illuminant as well as the ink colors. The figure shows the points as plotted for C. E. I. illuminant C which is the approximate equivalent of average daylight, having a color temperature of 6570°K. The color separation positives must all have matching gammas although slight overall variations in average density are permissible since adjustments of each individual illuminant level can offset such errors.

The density of developed separation plates as a function of a density of the gray-card used as a subject is shown in Fig. 18. Transmission differences for three plates

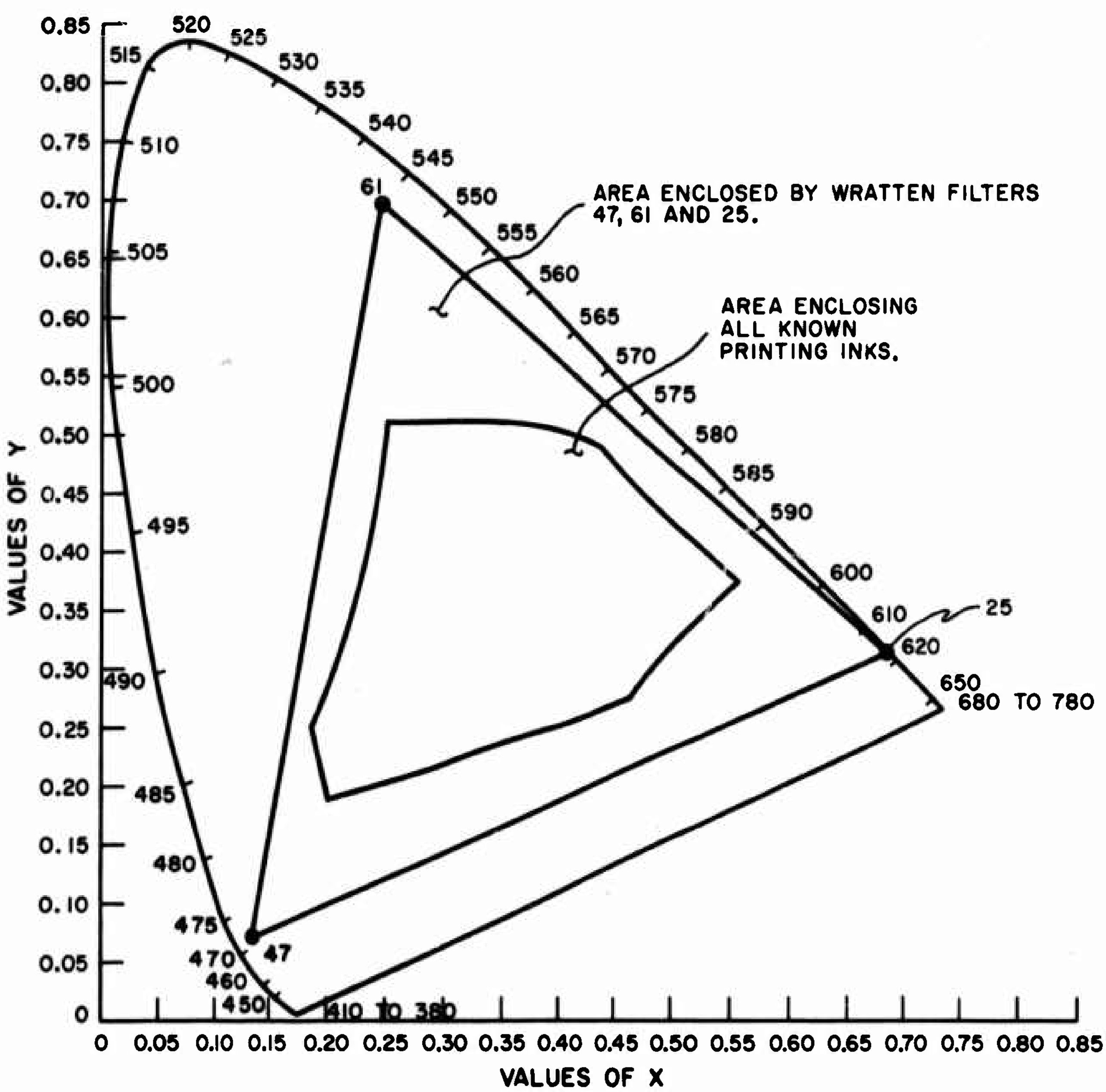

Fig. 17. Color coverage.

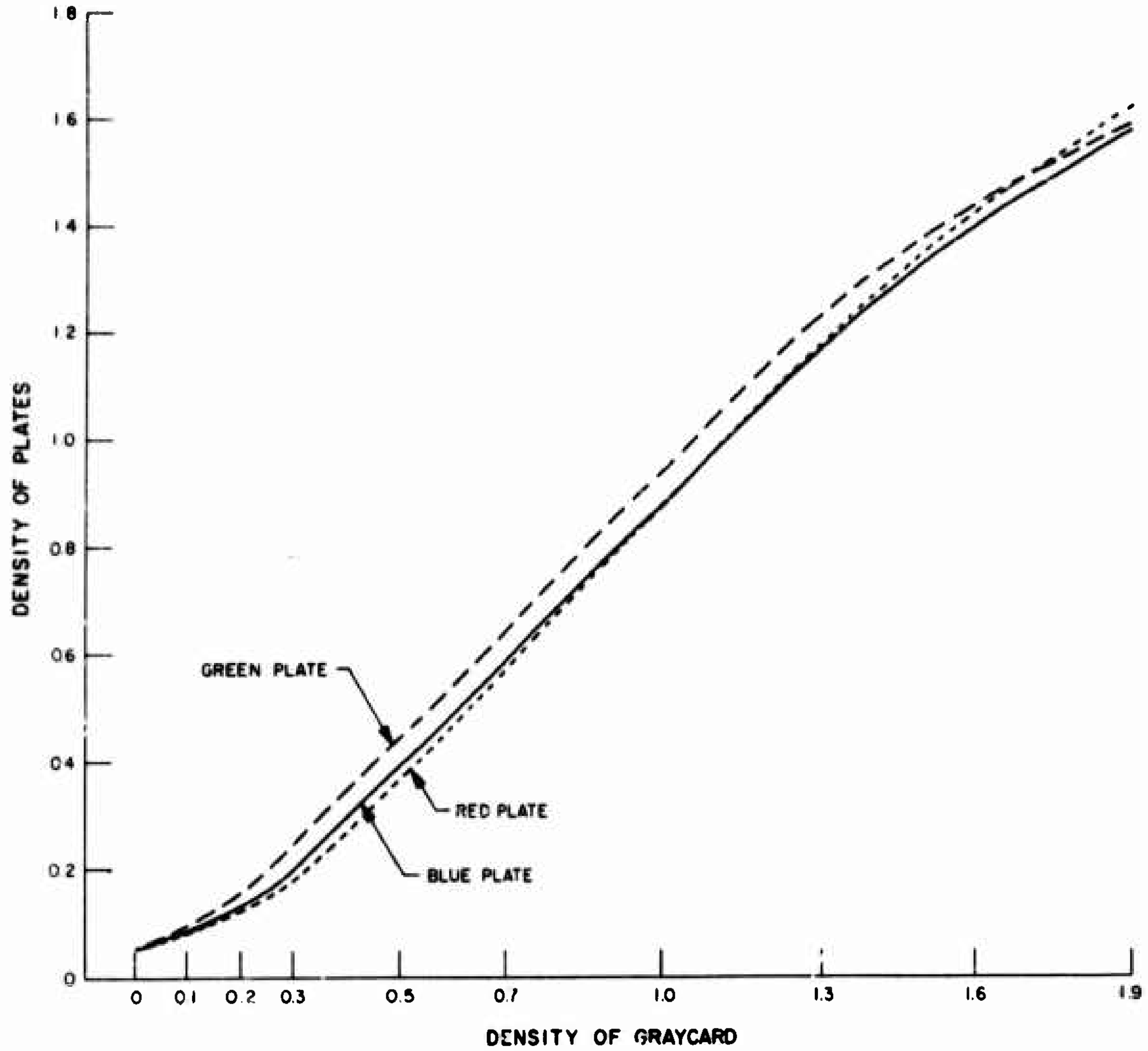

Fig. 18. Color separation plate densities.

when exposed through their respective color filters is shown in Table II. While the gamma does not match exactly, the maximum variation in light transmitted is only 8.4%. The effect of an 8.4% transmission error in color balance is seen as a slight hue shift in the grey steps 4 and 5, which appear to be just perceptably shifted toward the magenta when viewed as projected coincident images. By adjustment of the individual primary intensities, the projected gray scale can be made to appear gray on steps 4 and 5 and the darker steps appear to be gray also even though a small color error is present. This is because visual perception of small color differences depends on the apparent brightness of the subject, and if the subject is darker than a threshold value, the color is not perceived. The threshold for this effect varies not only as the luminence but also as the chrominance. In this case, the chrominance is small, i.e., the color difference from gray is small so that the perceptual threshold is high. The adjustment of primary intensities during projection to achieve gray in steps 4 and 5

TABLE II. TRANSMISSION THROUGH COLOR SEPARATION PLATES EXPOSED TO VARYING GREY SCALE DENSITIES

Step No.	Red		Green		Blue		Maximum Δ (%)
	Dens.	Tran. (%)	Dens.	Tran. (%)	Dens.	Tran. (%)	
1	0.05	89.1	0.05	89.1	0.05	89.1	0.0
2	0.08	83.2	0.10	79.4	0.09	81.3	3.8
3	0.12	75.9	0.15	70.8	0.13	74.1	5.1
4	0.19	64.6	0.25	56.2	0.20	63.1	8.4
5	0.37	42.7	0.45	35.5	0.40	39.8	7.2
6	0.57	26.9	0.65	22.4	0.59	25.7	4.5
7	0.88	13.2	0.94	11.5	0.88	13.2	1.7
8	1.18	6.6	1.23	5.9	1.17	6.8	0.9
9	1.42	3.8	1.44	3.6	1.39	4.1	0.5
10	1.62	2.4	1.59	2.6	1.58	2.6	0.2

results in the whiter steps of the gray scale being shifted toward the magenta, because the shoulders of the three curves have small slope differences.

Using red as a reference, a small green deficiency and a smaller blue deficiency exists. The range of tri-stimulus spectral compositions of light perceived as having originated from black bodies over the interval of temperatures from 1900°K to 20,000°K is considerable and yet the human eye can adapt itself to see them as white; i.e., to use any of these compositions as a reference against which the chromaticities of other stimuli are judged. In the case of the gray scale projected with an adjustment of primary intensities resulting in the perception of steps 4 and 5 as gray, steps 1, 2 and 3 also look gray since their chromatic errors are buried in the darkness of their shades and steps 6, 7 and 8 also look gray, but steps 9 and 10 would show a slight shift to the magenta. While the overall effect on reproducing the color content of the map of which the gray scale was a part is satisfactory, improvement can be made by better matching of the gamma curves on the three color separation positives.

The linearity of each step of the process from the initial exposure to the final hologram must be preserved to maintain color fidelity at readout. Positive transparencies can be obtained by either reversal processing or printing positives from original negatives. The choice of procedure should be made to insure the best overall linearity.

Compensation can be achieved by selecting appropriate portions of the H-D curves of a two-step film process as shown in Fig. 19. The negative has a linearity error causing density compressions near the shoulder of the curve. This negative is now printed and the resulting positive has less overall error since its linearity curve is such as to cause density compression at its shoulder. The compressed density of the negative becomes the extended density of the positive.

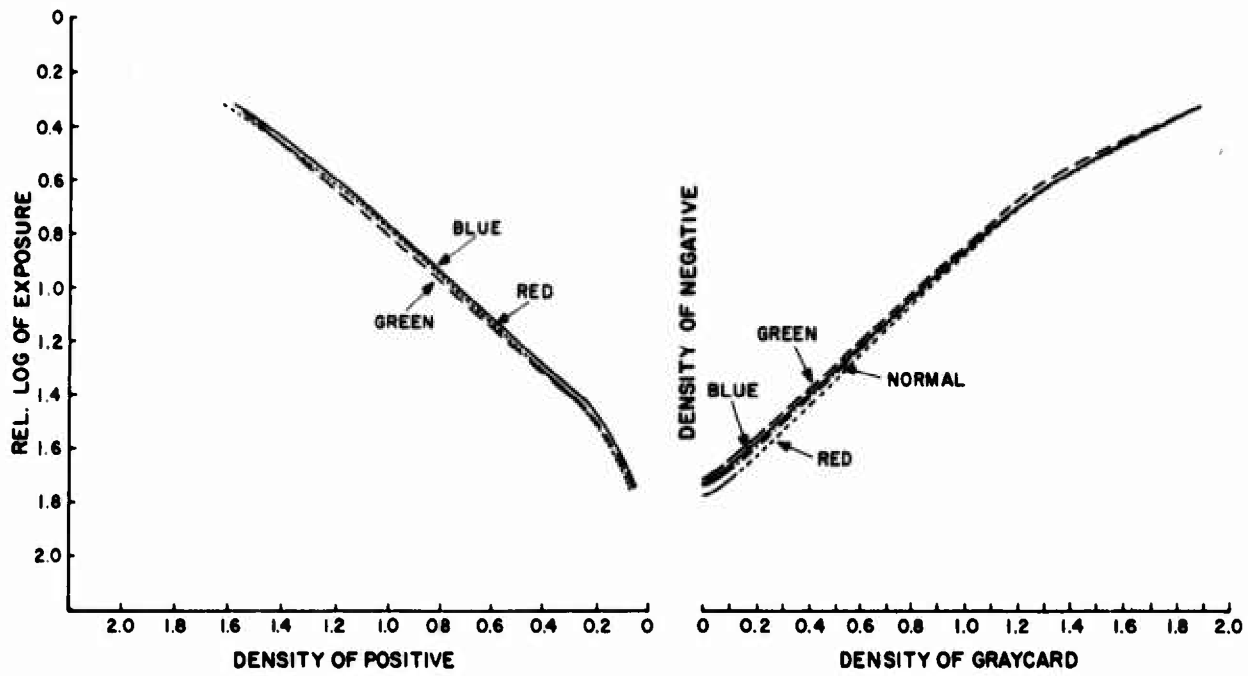

Fig. 19. Tone reproduction cycle

Deviation from linearity is seen to be less in the curve for the positive print. The curves may be made to shift gamma linearity changing time of development for a given density (exposure compensation is necessary) for each color. While this was not done in the preparation of the films used in the feasibility experiment, it appears to be a means of possible improvement in future programs.

Greyscale linearity must also be preserved in the holographic recording step. Photographic recording materials tend to be non-linear and the extent depends on many factors. Photoresists in general also fall into this category. The best photoresist found for this purpose is Shipley AZ-1350. The developer recommended by the manufacturer for this material is Shipley 1350 Developer; however, this combination results in a high degree of non-linearity. (Non-linearity is of negligible concern to users of these materials for purposes of photo-etching and photo-gravure.) Shipley AZ-1350 resist when developed in 303 developer gave improved results. An attempt to optimize this combination was made by studying the effect of time of development for a given surface depth modulation at various temperatures and dilutions using in each case a corrected exposure.

The deviation from perfect linearity over a depth modulation of three half waves of wavelength, $\lambda = 0.4416\ \mu m$ was unmeasurable. This condition was met by exposing for the time required to reach the above depth of $0.664\ \mu m$ when developed for 29

seconds in 4:1 developer at 20° C using ultrasonic agitation in the developer tank. The significance of the indicated depth is that 100% modulation of the refracted light by the grating takes place for a depth of $\lambda/2$ in reflection mode (and λ in the transmission mode assuming refractive index of the medium to be 1.5). Modulation other than grating modulation takes place also; i.e., scatter caused by substrate imperfections, coating inhomogenietics, and microroughness of the developed grating. These effects are small, variable and difficult to measure.

The ultimate color fidelity depends on the overall linearity and the enclosure of the printing ink trichromatic coordinates within the area bounded by the primary coordinates. These two conditions have been met very closely, as shown in Fig. 17, with Kodak Wratten filters 47, 61, and 25, but the linearity in the photographic steps can be improved.

The linearity of the hologram is essentially perfect if only one hologram is made in the frame area but since three separate holograms are superimposed in this area an effective non-linearity exists. This can be understood by considering the effect of two gratings of the same amplitude and spatial frequency but different meridian angles recorded on a hologram.

Let the hologram be representative of a field which contains 3 colors; primary 1, primary 2, and an area of overlap giving rise to a color formed from an additive mixture of primaries 1 and 2. The grating for primaries 1 and 2 are of maximum amplitude. The overlap region contains amplitude valleys which are twice as deep where the intensity maxima occur and peaks which are half as high where the intensity minima occur. The peak-to-valley amplitude in the overlap region is then the same as it is in the single primary region. However, since in the overlap region the intersection of the gratings results in the effective removal of volume from each by the other, the light refracted into the system will be proportionally reduced as a result of overlap. For example, if blue is orthogonal to green, the maximum intensity obtainable from the blue-green (Cyan) producing region is only half that obtainable from the blue and green producing regions. White is obtained by refraction from a triple-overlapped region and its maximum amplitude is only 1/3 that of its constituent primaries.

Color fidelity can be achieved only if the maximum intensities obtainable from all regions are equal. This condition can be obtained by using the technique of color mask compensation. The color mask can be made by first making the color separation negatives in the manner described above and then making a positive transparency printed from the three registered negatives. Now each separation positive is made by printing this mask in register with its primary negative.

The resulting separations will have corrected densities and system linearity will be preserved.

D. STORAGE MEDIA

Information may be stored in holographic form as a thick-on-thin, absorption or phase, transmission or reflective hologram. These are the fundamental characteristics which establish the suitability of a particular class of materials for use with a particular holographic form. The selection of a particular material having selected the general class of materials is dictated by tradeoffs which relate the following parameters:

(1) Resolution capability

(2) Diffraction efficiency (the ratio of the incident energy to that refracted into the imaging wavefront)

(3) Optical quality (the ratio of the energy incident on the image plane containing information to the total energy incident on the image plane)

(4) Sensitivity (energy per unit area required for formation of the hologram)

(5) Material availability and consistency

(6) Image permanence

(7) Material durability under expected environmental and handling conditions

(8) Cost (time and money) of producing a master and generating copies.

A discussion of the various materials available for holographic recording follows resulting in the recommendation that photoresist (Shipley AZ1350) be used as the basic recording material for storing the multicolor chart information.

This recommendation (discussed in more detail later in this section) is based on the fact that photoresist is an inexpensive, readily obtainable material which is essentially grainless, possesses low optical scattering and extremely high resolution characteristics. It records information as a surface relief image and as such can be interrogated either as a transmission or reflection phase hologram which can be used to control large amounts of optical power without dissipating energy. Recording information using a phase medium eliminates the common fault in high density storage of heating of the storage medium to the extent that information is destroyed. In addition, photoresist is one of the few materials which forms a relief image of sufficient depth that it can be used in an embossing process to form inexpensive copies.

1. Definition of Terms

Before discussing in more detail the materials available for recording, terms as used in this section will be defined.

a. Thick or Thin Holograms

Consider first the nature of the storage in the material. The information can be stored as a thick or a thin hologram. A thin hologram is formed when the fringe patterns comprising the hologram are stored on the surface of the recording material or when the thickness of the material containing the information is small compared to the wavelength of the optical signal used to produce the image. A relief hologram is generally a thin hologram and is formed when the fringe patterns comprising the hologram are recorded as surface deformations on the recording material. The depth of recording and efficiency of the hologram is this case depend on the physical characteristics of the material and the thickness of the medium.

Thick holograms are formed by recording information in a volume rather than as a surface or thin-film phenomenon. A thick hologram is one with a thickness greater (generally many times) than the wavelength of the illumination source. The hologram is composed of planes within the volume of varying density or index of refraction. For maximum efficiency (maximum reconstructed image brightness) the planes are spaced at distances which satisfy the Bragg condition.*

b. Absorption or Phase Holograms

Thick or thin holograms may be recorded using storage mediums which either produce a disturbance in a reconstructed wavefront by absorbing energy from it (an absorption hologram) or by affecting the phase relationships existing across the wavefront (phase hologram). In either case, energy is refracted into a wavefront which forms or can be acted upon by a lens system to form an image of the stored information. In general, for a direct-view high-brightness display generated from a high-information-density storage plate, phase holograms must be employed in order to prevent damage to the storage medium which results in loss of information. (The use of a non-energy-absorbing hologram prevents problems similar to those encountered in high-reduction microfilm systems, where the film overheats when an attempt is made to increase the brightness of the display.)

c. Transmission or Reflective Holograms

In addition to being classed as an absorption or phase hologram, the hologram may be transmissive or reflective. Absorption holograms are generally

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*The planes are spaced at a distance d where

$d = \nu\lambda/(\sin\theta + \sin\varphi_i)$

ν = refractive index of the material

θ = angle between the surface normal and the reference beam

φ_i = angle between the surface normal and the i^{th} component of the object beam

λ = wavelength of the optical signal.

transmissive, employing materials which absorb energy from the wavefront as it passes through the material. Typical examples are conventional silver-halide photographic films; in this case, energy is absorbed as it is transmitted through the medium to produce a refracted information-bearing wavefront. Photochromic materials behave in much the same manner.

Phase holograms may be made in either a transmission or reflection form. Photoresist is an example of a material which can be used to produce phase holograms. In its positive form, energy falling on the medium reduces its solubility in a developing solution, affecting the rate at which it is washed away when developed. Consequently, by limiting the time in the developer, the thickness of the material after development is a function of the energy falling on the medium. The photoresist, which remains on development, has an index of refraction different than that of the surrounding air; consequently, a wavefront passing through the medium experiences phase distortions, causing the generation of a refracted information-bearing wavefront. Or since the photoresist hologram is a relief hologram, it can be made into a highly efficient reflective hologram by metalizing the surface. Due to the variations in the surface level, energy will be reflected from the metalized surface, with phase perturbations causing an information-bearing refracted wave to be generated.

2. Recording Materials

The characteristics of materials evaluated under this program are listed in Tables III and IV. A discussion of the advantages and disadvantages associated with these materials follows:

a. Photoresist

Photoresist is a photopolymer; it has the property that the solubility of the material in an alkaline developing solution is a function of the exposure of the material to energy in the UV or deep blue portion of the optical spectrum. For a material such as Shipley AZ-1350, which is recommended for the moving map application, a positive effect is produced; that is, exposure to optical energy increases the solubility of the resist material in the developing solution.

The material is essentially grainless and has a resolution capability greater than 1500 lp/mm. For the moving map application, and in fact, for all but the highest resolution applications, system resolution is limited by the optics long before the resolution of the storage medium is approached.

Photoresist is a phase-recording material (as opposed to an absorption material), which can be used in either the transmission or reflection mode. When used in the reflection mode, the optical efficiency of the system is increased by lightly plating the developed material with a conductive reflector such as aluminum, gold, or silver.

TABLE III. HOLOGRAPHIC STORAGE MATERIALS

Material	Durability	Image Permanence Upon Readout	Availability and Consistency	Optical Quality	Relative Cost of Master and Copies
Silver halide	Good, but scratches easily	Long term but may damage with bright source	Commercially available, but a flat substrate is desirable	Grain noise very good but present even when bleached to form phase hologram	Expensive, silver halide film cannot be replicated cheaply
Photoresist	Excellent	Long term	Kodak and Shipley resists available but must be prepared on substrate for use (Kodak is preparing a material for commercial use)	No grain noise. Optical quality excellent. Very low scatter for surface holograms	Material costs less than silver halide, uses only one simple chemical solution for processing and low-cost embossing techniques for replication process
Dichromated gelatin	Fair, but sensitive to humidity and scratches	Must be stored under controlled humidity and temperature	Commercially available chemicals but must be prepared by user	No grain noise, but optical quality is high	Low material cost but complex fabication process adds cost. Cannot be replicated by embossing

TABLE III. HOLOGRAPHIC STORAGE MATERIALS (Continued)

Material	Durability	Image Permanence Upon Readout	Availability and Consistency	Optical Quality	Relative Cost of Master and Copies
Photochromics	Careful storage required	Short term	Some types may be obtained directly from vendors	Single crystals are grainless, but others have effects resembling film grain noise	No developing necessary, but there is no easy replication process and the material is expensive as processed for holography
Thermoplastics	Deforms with temperature	Degrades with temperature tends to cold flow with time	Thermoplastic must be overcoated with photoconductor and placed on conductively coated glass or Mylar substrate	Grainless, but limited resolution because of lateral heat flow during recording	Material is expensive but may use embossing for replication if master is metalized

TABLE IV. HOLOGRAPHIC STORAGE MEDIA PRESENTLY IN USE

Material[1]	Type[2]	Reconstruction Mode	Diffraction[3] Efficiency (percent)	Reported Sensitivity (J/cm^2)	Resolution (lines/mm)	Comments
Kodak 649*	Thin, absorption	Transmission	~6	$\sim 0.01 \times 10^{-3}$ at 6328Å	2000	Bragg condition always present to some degree
Kodak 649F Bleached with R10	Thick, phase	Transmission	45 to 50	10×10^{-3} at 6328 Å	2000	a) Lower grain noise than 649F b) Efficiency is compromise with optical quality.
Agfa-Gevaert 8E70 Bleached with R10	Thick, phase	Transmission	65	0.25×10^{-3} at 6328 Å	>1600	a) Thinner than 649F and hence less absorbing.
Agfa-Gevaert 10E75	Thin, absorption	Transmission	1	—	> 500	a) High resolution and sensitivity at 6328 Å b) Balance ratio of 7:1.
Agfa-Gevaert 10E75 Bleached	Thin, phase	Transmission	10	—	> 500	a) Balance ratio 7:1
Dichromated Gelatin	Thin, phase	Transmission	32	3×10^{-2} at 4880 Å	3000	a) No grain noise.
	Thick, phase	Transmission 1. Soft 2. Hardened	 96 80	$\left.\begin{array}{l}120 \times 10^{-3}\\ 3 \times 10^{-3}\end{array}\right\}$ 4880 Å		
KOR Photoresist	Thin, phase	Transmission or Reflection	5	1.3 at 4880 Å	1500	Diffraction efficiency depends on allowable intermodulation distortion.
Shipley AZ1350 Photoresist	Thin, phase	Reflection or Transmission	30	11.0 at 4880 Å 0.02 at 4416 Å	1500	
Thermoplastics	Thin, phase	Transmission	—	1×10^{-3} at 6328 Å	1000	Resolution is function of quasi resonant frequency of thermoplastics

NOTES:

* Kodak High Resolution Playe Type SO-343 with 649GH emulsion has similar characteristics although it has spectral sensitivity up to only 6000 Å.

1 The materials and pertinent characteristics listed have either been reported in the open literature or have been achieved by RCA.

2 A phase hologram has higher efficiency than an absorption type, and a thick hologram has higher efficiency than a thin hologram of the same material.

3 Diffraction efficiency =% of incident laser beam diffracted into first order.

A major requirement imposed on the recording material, as indicated in Section IV.C, is that the material be capable of recording multiple exposures without generating cross talk intermodulation components between the exposures. This imples that the material possess a linear exposure versus solubility curve over a wide range of exposure. This property is one of the major factors influencing the choice of photoresist and in particular AZ-1350 over more conventional recording materials (such as the silver halide material). If a silver halide material were used for the exposure of the first object, exposure to a second object would severely degrade the first latent image. This degradation results because the second exposure is not coherent with the first. Consequently, the effect of the second exposure is to fog the first; similarly a third exposure would further degrade the hologram. With photoresist, the fogging effect is not produced. The effect of multiple exposures is to cause a reduction in the thickness of the photoresist without changing the form of the information previously recorded. This condition holds as long as the cumulative exposure levels remain within the linear response area of the photoresist material. Individual component exposure adjustments can be made to partially compensate for curve nonlinearity with photoresist.

A sensitivity curve as a function of wave length is shown in Fig. 20 for photoresist and dichromated gelatin in the deep blue portion of the spectrum. If the 4416 Å line of the HeCd laser is used for exposure, the photoresist has a sensitivity of 0.025 J/cm^2 for the production of an optimum grating; i.e., a grating having a depth which most nearly approaches that required to produce maximum diffraction efficiency. Required exposures of this level are readily available in the experimental set up used to demonstrate the feasibility of recording multicolor map information. When recording the map information, exposures 1/3 the optimum are employed and a reduction in diffraction efficiency accepted so that three non-interferring holograms may be recorded in a common area. When recording using a 15-mW HeCd laser on a 3/8 by 3/8 in area, exposure times of the order of a second are required for each of the three color separations.

An additional and major advantage of using photoresist is that original master holograms generated as surface reflief images on photoresist can be duplicated on vinyl material. A replication process has been developed by RCA on an internally funded program for commercial application. This process is directly applicable to the moving map application. Replication on vinyl provides a hologram which is (1) rugged and scratch, abrasion, and water resistant; (2) inexpensive; and (3) readily replicated by a simple embossing process.

The steps in the production of vinyl holograms are as follows:

(1) A mylar substrate is coated with photoresist (the depth is immaterial as long as it exceeds several micrometers).

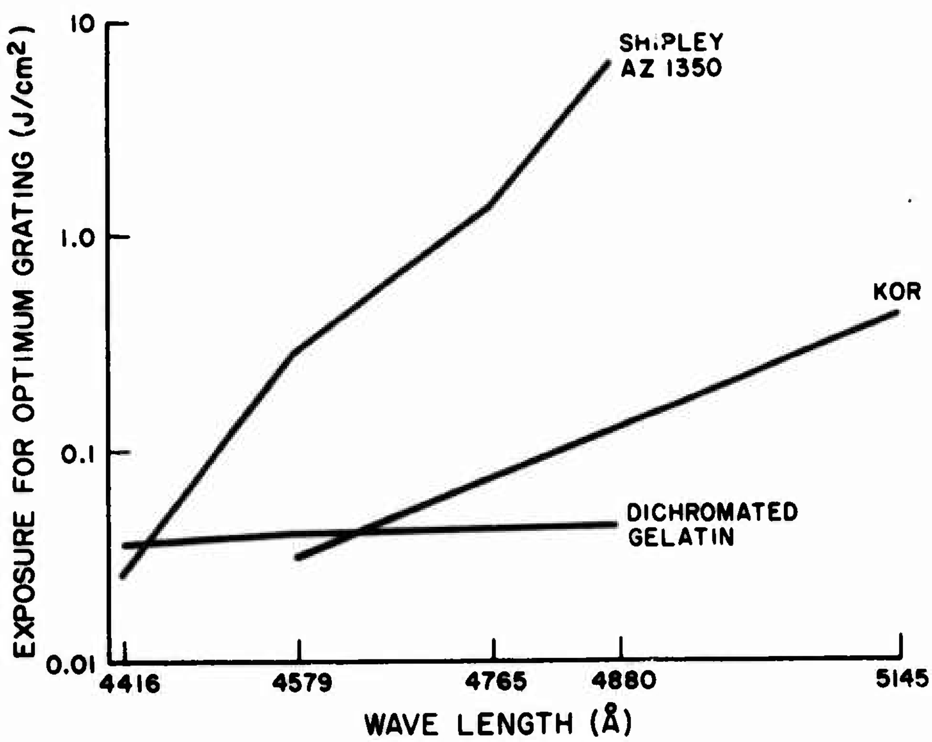

Fig. 20. Photoresist and dichromated gelatin sensitivity as a function of wavelength.

(2) The photoresist is exposed by a holographic interference pattern formed in blue light.

(3) The exposed material is processed in an alkaline developer, rinsed with water, and dried.

(4) The hologram is plated with nickel to a thickness of several thousandths of an inch. The thickness is not critical but it must be thick enough to allow pressing the vinyl.

(5) The photoresist-coated mylar is stripped from the nickel layer.

(6) The nickel layer is used to impress its surface modulation on a thin film of polyvinylchloride. This requires a temperature of about 100°C.

The pressing may be done by passing the nickel master and the vinyl film through pinch rollers at speeds of several feet per second. Nickel masters of this type have been used tens of thousands of times with no noticeable deterioration.

The steps of the duplication process are as indicated in Fig. 21.

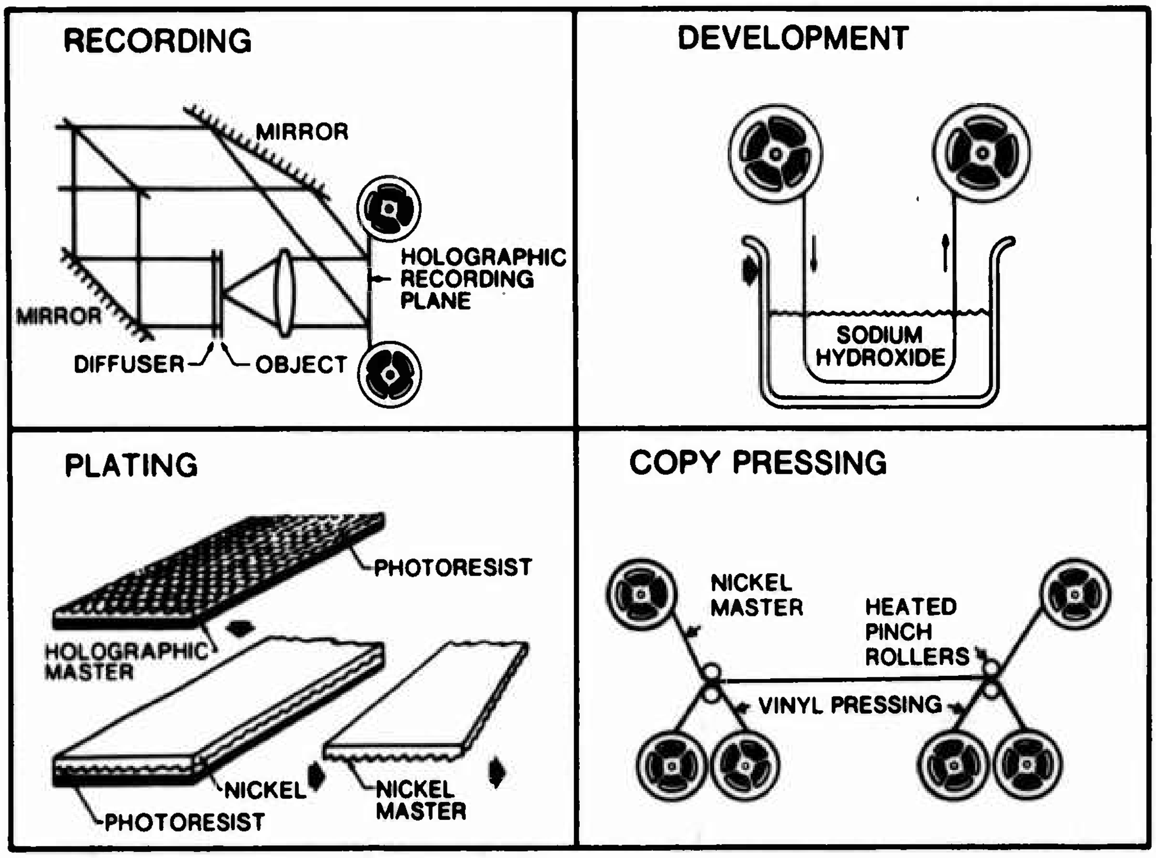

Fig. 21. Duplication process.

The advantages associated with photoresist as compared to other recording materials when coupled with the fact that the required exposure levels are well within acceptable practical levels has led RCA to recommend that this material be used for multicolor moving map display applications.

Other material considered and discarded are discussed below.

b. Silver-Halide Emulsions

Silver-halide emulsions are widely used for holographic recording. Films such as Kodak 649F (for recording in the long wavelength portion of the optical spectrum) and 649G (for recording in the blue and gree portions of the spectrum) are typical of high-resolution films employing standard processing techniques which exhibit good long-term storage qualities and high resolution. Holograms stored in emulsions of this type are transmission types and store information as absorption variations within the medium. Diffraction efficiencies of the order of 6 percent into the reconstruction order are typical. Although normally considered to be stored in a relatively thin emulsion, Bragg effects due to emulsion thickness can cause an

increase in efficiency; such holograms, however, have been reported to be highly astigmatic for even small angular changes in the reference beam. When forming transmission holograms with silver-halide emulsion, care must be taken to eliminate unwanted phase variations due to thickness variations and stresses in the material. This is accomplished in some instances by using micro flat glass substrates.

By bleaching out the silver halide after exposure, volume or thick phase holograms have been made having a 45- to 50-percent diffraction efficiency at 6328 Å. Images of high quality with low grain noise can be obtained by this method. A theoretically available diffraction efficiency of 100 percent for the volume phase hologram has not been realized for this case due to the partially absorbing character of the bleached emulsion. The optimum exposure was found to be a compromise between high efficiency and optical quality. It has been shown that the basic mechanism for phase change in the formation of a relief image is by the bleaching process and small index variations.

In addition, Agfa Gaevaert 8E70 and 10E75 are thinner silver-halide emulsions, having higher sensitivities and higher diffraction efficiencies. Both have been used to store both bleached and unbleached holograms.

To interrogate the hologram in the transmission mode, a reconstruction beam is transmitted through the medium. The variation in thickness of the photoresist material which has an index of refraction different than that of the surrounding medium (air) causes a perturbation in the phase of the wavefront as it passes through the medium. The phase perturbation produces an information-bearing refracted wavefront.

An alternative method of forming the image is to reflect energy from the deformed surface. The surface deformation produced by the removal of the photoresist material produces phase perturbations in the reflected wavefront. The efficiency in the reflected mode is enhanced by depositing a highly reflective metalization layer on the embossed surface. The manufacture of the hologram in this fashion can lead to the development of holograms with diffraction efficiencies approaching 34 percent.

The method of forming (reflection or transmissive) holograms by surface deformation has an inherent advantage over other forms of holographic construction; it can be easily replicated by an embossing process similar to that employed to press phonograph records. A practical implementation of this technique has recently been unveiled by RCA in a holographic storage system for the home storage of television program material. In this system holograms are replicated by hot embossing vinyl tape from a nickel-coated photoresist hologram master.

A comparison between two of the more popular resist materials, KOR negative resist and Shipley positive resist, indicates that the KOR (although more sensitive than the Shipley) had lower diffraction efficiency, especially at high spatial

frequencies. In this regard, the Shipley was found to offer a better compromise between efficiency and distortion than KOR. Diffraction efficiencies as high as 30 percent at 1500 lines/mm were obtained in the Shipley material. However, a more realistic efficiency is 8 percent when low intermodulation distortion* is desired.

c. Dichromated Gelatin

The construction of phase holograms with high-diffraction-efficiency dichromated-gelatin films has been reported. Diffraction efficiencies of 96 percent for a thick hologram and 32 percent for a thin hologram (both used in the transmission mode) have been obtained. The diffraction mechanism is produced by large variations in the refractive index of the material upon exposure, without the complicating presence of silver halide. Grain noise is absent; however, materials utilized to date possessing high diffraction efficiencies exhibit a whiting effect (forward scattering; e.g., opal glass), which tends to degrade the optical quality**of the image. The gelatin is much less sensitive than the photographic emulsions and, for the materials considered, is totally insensitive at wavelengths longer than 5500 Å. Relief or surface holograms have been made from dichromated gelatin but have not been reported with high efficiency or high resolution.

d. Photochromics

A number of organic materials and a large number of organic dyes possess an ability to exist in a stable form in either a colored or uncolored state. A change from one state to another can be accomplished by exposure of the material to light of a specific wavelength (color). The material can be restored to its original wavelength by exposure to a different portion of the spectrum or in some cases by heat.

The materials are capable of storing information at high resolutions, require no development, and can be corrected or reused. Further photochromic materials offer the possibility of volume recording in which many (perhaps 100) holograms are stored in a compact volume. Readout is accomplished by varying the incident angle of the reconstruction beam. However, the information tends to degrade with time and use. Presently, materials are available having storage shelf lives of the order of months but only when stored in controlled environments. The photochromic materials can be used only as an absorption medium in the transmissive mode; the information is not stored as a relief image and therefore cannot be easily copied (i.e., embossing is not possible).

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*Intermodulation distortion produces random fringe patterns in the reconstructed image.

**Optical quality as used here is related to the ratio of the imaging information refracted to stray energy traveling in the same direction.

Research programs are being actively pursued to develop stable high-resolution photochromic material. It is the authors' opinion that it is only a matter of time until these materials become available for applications of this type. However, such materials are not now available.

e. Thermoplastics

Thermoplastic materials are also capable of forming relief holograms. Thermoplastic recording is accomplished by depositing a charge pattern on a material which deforms when heated. If a conductor is placed on the side opposite the deposited charge and grounded and the material is heated, it will deform, compressing where the charge has been deposited. As the material is cooled, the information will be "frozen" in the surface deformation.

A hologram can be formed upon exposure to optical energy by employing the sandwich arrangement indicated in Fig. 22. Here the thermoplastic material is coated on one surface with a conductor; the opposite side is coated with a photoconductor. A uniform charge is deposited on the surface of the photoconductor and the material heated. The holographic refraction pattern then exposes the photoconductor, causing the charge deposited on the surface to be redistributed on the thermoplastic material in accordance with optical energy distribution. Thermoplastic phase holograms have been made using this technique. Resolutions as high as 750 to 1000 lines/mm have been realized. Sensitivity for nominal depths of recording are of the order of 1 mJ/cm^2, which is adequate for holographic recording purposes.

The material, however, tends to flow and deform during storage (even at low temperatures), resulting in poor image stability. In addition, the material when used for optical recording is considerably more expensive than silver-halide recording materials.

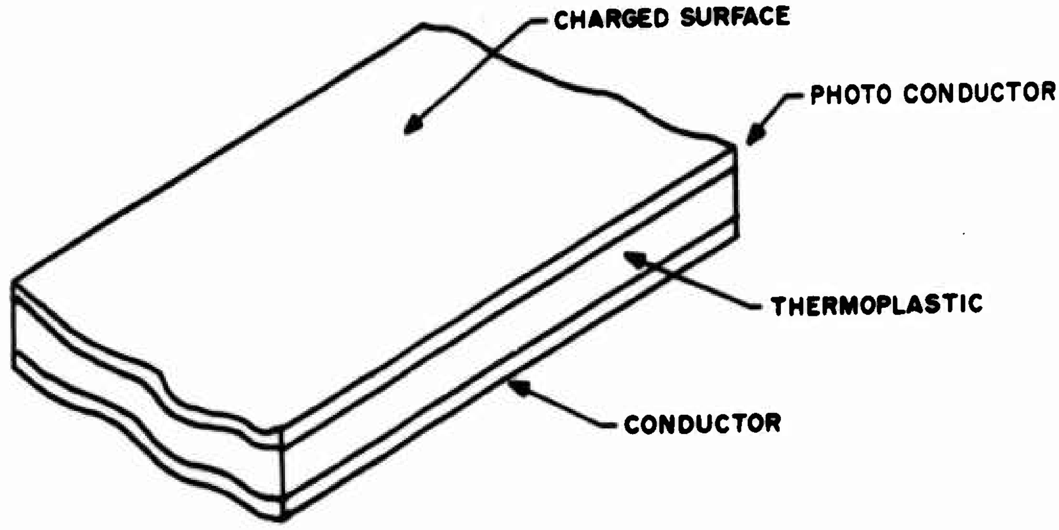

Fig. 22. Thermoplastic sandwich.

f. Volume Storage Materials

Little emphasis was placed during this study on the investigation of volume storage materials; i.e., materials such as lithium niobate and strontium-barium niobate. Although these materials offer the potential for storing large amounts of data in small volumes the state-of-the-art of the development of these materials has not progressed to a degree that would allow their use for the generation of high quality displays of the type required for the moving map display. Deficiencies in the materials include imperfections (strains, discontinuities), which appear as blemishes in the projected display; storage times of limited length (order of hours, when storage times of days and preferably weeks without noticeable degradation are required); and image degradation upon readout. Further, with the technology presently available the generation of duplicate copies is time consuming and expensive.

RCA does realize, however, the significant advantages associated with the high volumetric efficiency associated with the volume storage material, and is consequently actively engaged in the development of volume storage material for applications of this type. A major portion of this work is being done in conjunction with the Navy under contract N62269-70-C-0372, "Exploratory Investigation of Holographic Storage in Crystals for Moving Map Display."

E. RETRIEVAL

A major advantage of holographic recording of the moving map information lies in the fact that digital information describing the map can be stored in the same area used to store the map information. The information can then be used in a rapid-access system to allow retrieval of a particular map from a collection of maps. It is recommended that this so-called data block information be stored over the map information as a Fraunhofer hologram. The Fraunhofer hologram offers a unique advantage over other hologram forms* in that the reconstructed image is fixed in image space even as the hologram is translated with respect to the readout system. This enables binary coded information to be holographically recorded such that upon reconstruction the binary bits will be fixed in image space as the frame moves through the film gate. A detector matrix placed in the focal plane of the readout lens is assured of operation without the alignment errors that usually result in a conventional system as a result of film transverse wander, vibration or lack of longitudinal film registration.

This important benefit of Fraunhofer holography greatly relieves the following three stringent requirements normally associated with optical retrieval systems.

*The Fourier-transform is a special case of the Fraunhofer hologram and also exhibits this effect.

(1) The alignment of the binary image on the detector matrix must be very accurate in X, Y and Z.

(2) The film velocity must be such as to allow the detectors and associated circuitry to operate within their passbands. This imposes a limit on the film velocity since the ratio of allowable film frame area containing stored data to that fractional area containing the frame address imposes bit image size restriction. The resulting detector-recognition duty cycle is often such as to necessitate operation at the widest possible bandwidth of the detectors. Operating the detectors near their upper frequency cut-off generally affects the signal-to-noise ratio (SNR) adversely.

The image immobility of the Fraunhofer hologram allows a greatly lengthened duty cycle because the address signal remains on the detectors for a period almost as long as a frame interval.

(3) The coded address must be read without obfuscation by scratches or deletion by dirt particles.

Another property of the Fraunhofer hologram that is advantageous in this application is that it has maximum redundancy.

The redundancy is such that an object resolution element is recorded over an area determined by the focal length of the transform lens and the diameter, D, of the lens aperture, as shown in Figure 23.

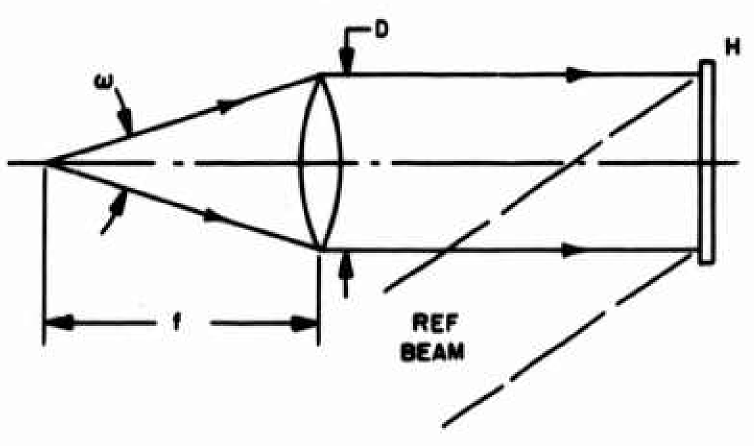

Fig. 23. The Fraunhofer hologram.

The diffraction angle, ω, is determined by the diameter of the resolution element, d, and the wavelength of the object beam λ.

$$\omega = \frac{2.4\lambda}{D}$$

where ω is the angle to the first minimum. In order to collect all light bounded by the first minimum the lens aperture, D, must be:

$$D = \omega f.$$

The light from the aperture is then collimated and the hologram area needed for this one point is approximately the area of a circle of diameter, D. This holds for an element on axis. The hologram dimensions for collecting off-axis points must be increased directly as the angular field of view.

Since an object resolution element produces an intensity distribution in the Fraunhofer plane that is a function of X, Y; and since the general object consists of a multiplicity of object points, the intensity distribution will be the complex coherent superposition of all such points. The information density per unit area on the recording surface will vary as a function of position. In order to conserve film area, the information density per unit area should be constant and should be related to the resolution capability of the film.

The use of diffuse objects or the combination of a diffuser with specular objects can bring about this condition and because of greater area utilization, higher optical efficiency can result, but, unfortunately, at the expense of speckle noise generation. Both the object information and the noise must be recorded in the film area; therefore, the area must be increased over that previously indicated. If the increase in area is just sufficient to maintain the same information density as before, the reconstructed image will be less satisfactory because the noise will also be reconstructed. Filtering out the noise can be accomplished in principle by reconstructing the hologram with band-limiting aperture that will pass the highest object frequencies but attenuate the higher frequency noise. The limiting aperture, hence, is the hologram itself and so must be increased further. However, the reconstructed image from a diffused object hologram has less contrast than an equivalent specular object hologram because not all of the random noise effects are filtered out in practice. An additional consideration is that the maximum size of the speckle grain recorded is inversely proportional to the limiting aperture of the system; therefore, in order to minimize the speckle grain size to values that are unobstrusive at readout, the hologram which is often the limiting aperture must be made considerably larger than recording medium resolution would dictate.

In general, the chief advantage of using diffuse rather than specular recording is that in the former a portion of the hologram can be obscured or excised with consequent loss in contrast and resolution in the restored image but with no losses that are a function of position. Excision of a portion of a Fraunhofer hologram of a specular object will result in degradation which is a function of position. Those portions remaining give rise to high contrast and sharpness in corresponding portions of the reconstructed image, but obliterated areas of the hologram produce corresponding image areas of negligible content.

If any of the binary bits comprising an address code are absent due to holographic record obliteration, the frame corresponding to that address cannot be retrieved. It is of paramount importance, then, that the redundancy be maximal. This can be done by: (1) using redundant coding of the address or (2) by recording the address over the largest possible area and with constant information density in the available area. If a diffuser is used with the objective to achieve this, the resulting random optical noise may give rise to electrical noise that because of its bandwidth will be difficult to filter out. However, a means of overcoming the random nature of this noise has been worked out be RCA and is known as the multiple object beam technique*. This method divides the object illumination beam into a number of discrete beams incident on a specular object each from a different direction.

One means of obtaining the desired number of object beams and the desired angle for each is to insert a diffraction grating in the object beam at a position just ahead of the object. The grating characteristics can be chosen, for example, to provide nearly equal energy in the + 1, 0, and -1 orders, and, if the grating is two dimensional, nine equal-intensity beams result. Special techniques allow usage of 30 or more beams. Each object beam produces a separate diffraction pattern of the object on the recording plane. The path length for a given transform lens is chosen to cause the multiple beams to produce separate object diffraction patterns adjacent to each other but not overlapping. This process may be thought of as controlled or ordered diffusion as compared to the random diffusion produced by ground glass or flashed opal glass devices.

The reconstructed image will have noise that differs from speckle noise in that it is not random. Here, the noise takes the form of a superimposed sampling grating. The sampling grating frequency may be chosen by making multiple object beam grating frequency an appropriate value.

The sampling frequency is chosen to be higher than the highest object frequency component in order to preserve detail.

As the film moves through the detector field, the sampling frequency is converted to an electrical signal dependent on film velocity and image spatial frequency. Electrical processing of the signal can enable effective removal of this narrow band noise.

<u>The preferred holographic record of the address block, then, is a Fraunhofer hologram with ordered diffusion using maximum recording area.</u>

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*William Hannan, "Elimination of Speckle Noise in Holograms with Redundancy," <u>Apl. Opt</u>. 7, 2301-2311 (1970)

The readout source for such a hologram must be coherent both spatially and temporally. Three possibilities exist for its practical implementation: (1) A collimated and filtered white light, (2) a laser, and (3) a light-emitting diode.

High holographic redundancy requires high coherence in the readout beam. A white-light source can be processed to give it a degree of coherence.

Spatial coherence is a function of beam collimation. Extended sources cannot be well collimated; therefore, point or quasi-point sources must be used. The collimated beam is now given temporal coherence by passing it through a narrow-bandpass filter.

The narrow-bandpass filter may be either of two types; a multilayer thin-film filter, or a prism or diffraction grating acting as the dispersing element in a monochrometer. If the grating is used only as a wavelength dispersing element, its spatial frequency is not necessarily the same as that of the hologram. Collimation of conventional sources such as incandescent lamps or even short, high-pressure plasma arcs is, in general, an efficiency losing process unless the size of the source is small enough to allow the required degree of collimation.

In addition to this loss, the monochromatization step also results in loss of light. The narrower the bandpass, the less the light from a given source.

Temporal bandwidth can be traded, however, for specific angular dependence of wavelength.

A hologram which contains its information as modulation of a carrier that is characterized by the strict linearity of its associated fringe pattern may be reconstructed with various wavelengths provided that each wavelength is incident at an angle θ such that $\sin \theta = \lambda \nu$ where ν is the spatial carrier frequency of the hologram and λ is the wavelength of the incident reconstruction beam. For example, the reconstruction beam angle for blue is less than that for red according to the relationship.

$$\sin \theta_b = \frac{\lambda_b}{\lambda_r} \sin \theta_r$$

where θ_b is the angle for blue, θ_r is the angle for red and λ_b and λ_r are the wavelengths for blue and red, respectively. If such a pre-dispersal grating is placed in the reconstruction beam, reconstruction incidence is corrected for every wavelength.

For a Fraunhofer hologram, the image centers for each wavelength would be made coincident by the pre-dispersal grating but the shorter wavelength images would be smaller than the longer wavelength images by the ratio of wavelengths. Thus, the readout band-pass cannot be traded for angle except for quasi-focused image hologram restoration.

For Fraunhofer reconstruction the light losses incurred in the collimating process are a function of source size and permissable divergence. In order to adequately resolve a bit spot diameter of 1 mm on the hologram, the collimation accuracy would have to be sufficient to allow a reconstructed image spread no larger than 0.5 mm. The bit size is arrived at as follows:

Fifteen binary digits can specify 32,768 different maps. While this number of maps is probably more than necessary for any mission, it is a number which reflects the system potential and will be considered in estimating the resolution of the retrieval optics. The 15 bits can be formated in 3 rows of 5 bits each with a blank space between each bit and between rows of bits, and since spaces and blank spaces are equal, the hologram area is divided into 6 rows of 10 spaces. A bit space of 1 mm^2 requires that the total coded area be 6 by 3 mm. Allowing a degradation of 0.5 mm, the collimation error angle can now be determined.

The angular subtense, α, of the allowable spot degradation at the detector is:

$$\alpha = \frac{0.5 \text{ mm}}{f_1},$$

as shown in Fig. 24. This angle, α, is the collimation angle. The image of the light source on the detector has a diameter defined by $j = \alpha f_1$.

The light source diameter, g, which provides this angle is:

$$g = \frac{f_2}{f_1} j.$$

$$g = 2 f_1 \alpha j.$$

The detector aperture diameter, j, is provided by the diode matrix spacing. The amount of optical power, W, collected from the source by the reconstruction beam collimating lens is:

$$W \approx W_l \frac{d^2}{16 f^2}$$

where d is the collecting aperture diameter, W_l is the source power, and f is the local length. Not all the light collected will be delivered in the specified collimation angle α, however, if the source diameter is larger than g. A tungsten filament having an area of 1 mm^2 operating at 2,700°K radiates 160 lumens into 4π sterations. Of this amount, the radiation collected by a lens with an aperture diameter of 10 mm and a focal distance f_2 of 30 mm is approximately 1 lumen.

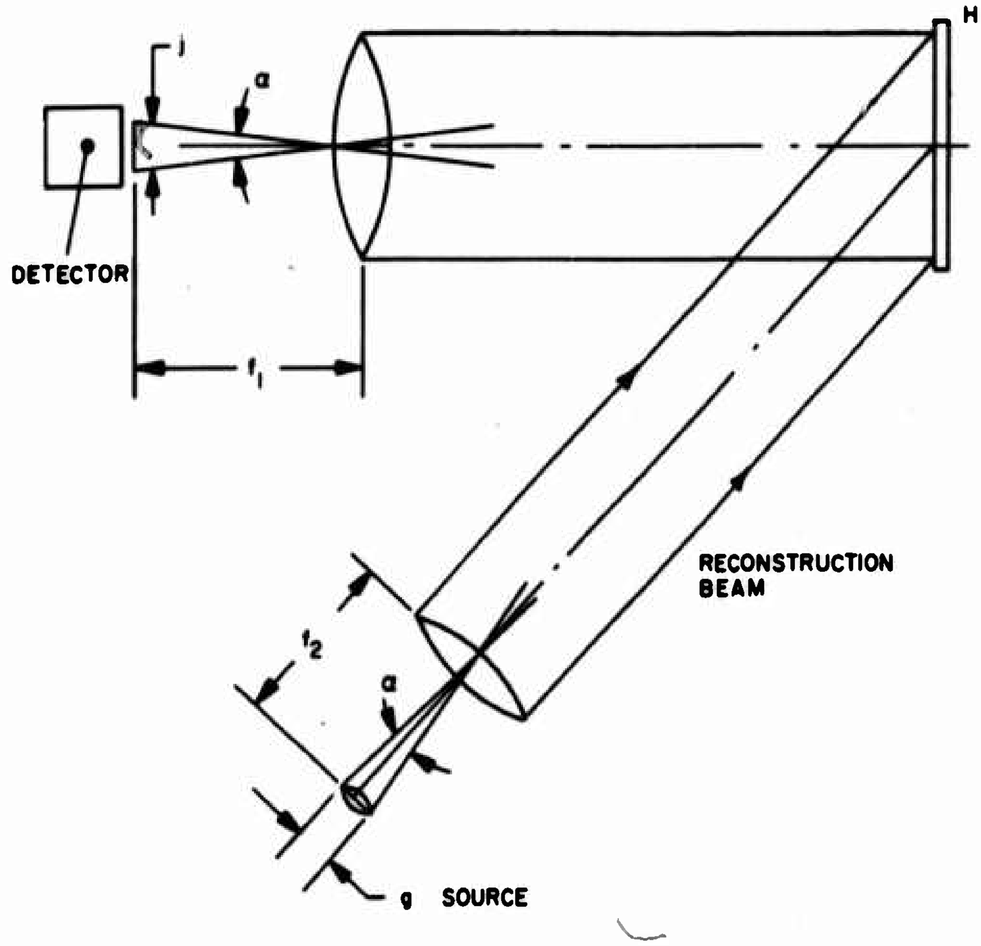


Fig. 24. Data block readout.

The source size of 1 mm is such that the collimation angle is correct for a 30-mm collimation lens working into a 15-mm transform lens. The overall optical efficiency including the transmission of the lenses, the reflective losses and the hologram efficiency is about 10%. The light incident on the detector would then be 0.05 lumens.

Another loss occurs, however, as a result of monchromatizing the beam. The transform lens focal length is 15 mm which produces the allowable 0.5 mm error at the detector for an error angle $\Delta\theta$ of .033 radians.

Grating dispersion δ is: $\delta = \frac{d\theta}{d\lambda}$ and if the spatial carrier frequency of the hologram is 600 cycles/mm, its first order dispersion is $0.6/\mu m$. The bandwidth, $\Delta\lambda$, producing an angular change of 0.033 radian is then

$$\Delta\lambda = \frac{0.033}{0.6/\mu m} = 0.055\ \mu m$$

The effective fraction of the light transmitted through a filter of this bandwidth is approximately $\frac{k\ 0.055\ \mu m}{0.25\ \mu m} \approx 0.02k$ where k a factor less than unity which results from the filter passband shape deviation from a perfect rectangular function may be taken as 0.5 and the light transmitted is approximately 0.01 of the input.

The total through-put considering both collimation losses and filter losses is then 0.0005 lumens (0.05 lines x 0.01). This value, while small, is adequate to obtain a sufficient signal-to-noise ratio from silicon detectors if care is exercised.

An alternative light source that would be more efficient in producing the requisite collimation since it is quite small and would not require a filter with its attendant losses is a light-emitting diode. Silicon diode detectors are sensitive to the 0.9 μm range emitted by these devices. Solid-state drivers for the diodes make the total package relatively small and lighter in weight than the comparable filtered, collimated incandescent package if a separate source is used for the address block rather than the primary readout bulb. The final decision as to which source is more appropriate in a packaged unit should be made during the mechanical design layout phase of a later program.

F. IMAGE MOTION

To be effective as a navigational display, it is essential that the displayed information be capable of moving under external control. For an aerial chart display, a mode of operation is desirable in which the map moves under the control of the navigation system an in a manner to maintain the aircraft position at some prescribed position on the display screen. In addition, it is desirable that the display be oriented such that either a "track up" or "north up" display be provided. Consequently, it is required that the displayed image be translated in X and Y and that it be rotated about the map center.

1. X-Y Motion

As described in Section III, one of the prime considerations in the selection of the holographic technique was the ability of the displayed image to move in accordance with motion of the holographic storage medium. Early in the program, various techniques were considered for providing image motions. Several mechanical deflection techniques were considered and rejected as being too complex and unreliable. A decision was made that the selected holographic storage technique must provide image motion in direct proportion to the motion of the medium. This is the condition which exists in a conventional photographic system.

The quasi-focused image hologram does produce image motion in direct proportion to the motion of the storage medium. Consequently, for this reason as well as others stated earlier, it was recommended that the quasi-focused image hologram be employed.

A dual-action transport system is recommended. As specified in Section V a cassette storage system which stores maps on reeled vinyl tape is recommended. If maps were selected in sequence as indicated in Fig. 25, continuous motion would be provided in East-West direction (X- direction for North up case) with adjacent maps butted and registered such that a discernible discontinuity is not apparent over a span of perhaps thirty maps in a cassette containing 500 maps. Map motion in the North-South direction would require that the storage tape be advanced by a discrete amount (30 map elements) and registered.

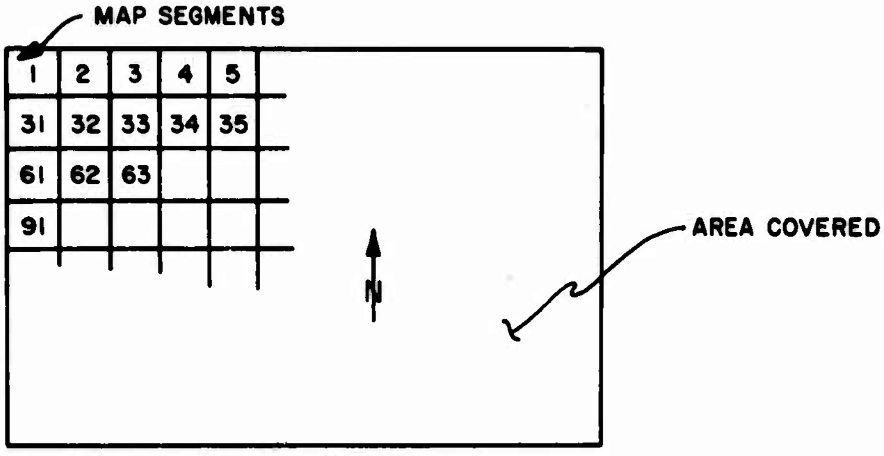


Fig. 25. Map selection sequence.

Map motion in the East-West direction is most easily accomplished by acting upon the transport system used to select the desired map. Two tape drive motors are used to position the map. These motors are activated to select the proper map and to position the selected map in accordance with an external control signal. Consideration has been given to the nature of the control signal used to position the map. The map is first selected using as a reference the data block interrogation system described in Section IV.E.

Precise position of the map information can be derived using a precision sprocketed storage medium and a sprocket wheel decoder. The sprocket wheel is used to drive an encoder which produces an output voltge proportional to the shaft position. In operation an error signal is derived by comparing this signal with a position indication signal supplied either from the front panel or a controlled input.

Position in the North-South direction is established by moving the complete cassette. As opposed to the East-West motion control, the film motion here is accomplished in an open loop fashion. The film cassette is precisely mounted on a registration plate. (Registration pins are used for this purpose to provide for quick mounting.) The plate is then translated to translate the image. As before, the displacement signal is derived from the position of the shaft. This signal is compared with a position level indication.

Although a variety of alternative registration techniques, including holographic techniques, have been investigated, further investigation is needed in the area before a prototype system is constructed. A laboratory demonstration unit of the type described in Appendix A can be constructed using these techniques, since in this system there is no requirement for an automatic registration system.

2. Image Rotation

The rotation of the optical image is most easily accomplished by the insertion of an image rotating element in the optical path. The major alternative is to rotate the hologram. Rotation of the hologram, however, is deemed impractical since this implies rotating the optical sources and the development of an unduly complex transport mechanism.

A variety of optical elements were considered. Elements such as K mirrors and Abbe and Pechan prisms appear to be the most practical. All three elements are similar in concept and produce rotation of the image by rotating the prism about the optical axis.

Consider the K mirror arrangement shown in Fig. 26. The mirror structure produces an reverted, or mirror image, of the original object as shown in Fig. 26a. The structure has the property that it can be used in either collimated or uncollimated light.

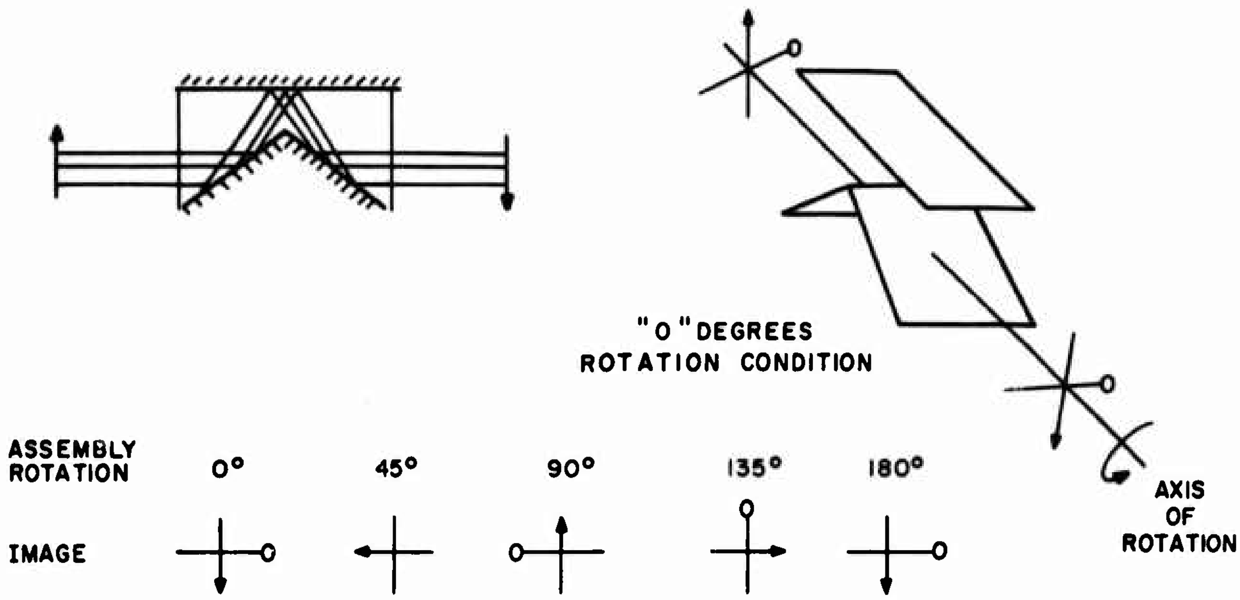
A particular mirror configuration designed for use in the moving map projection system is shown in Fig. 26 b and c. The effect of the rotation element on the optical path length is shown in Fig. 26b, and the mirror configuration for the display system proposed for the laboratory mode is shown in Fig. 26c. The highly reflective mirrors are formed by metallizing the reflecting surfaces. The internal portion of the structure is void so that the optical signal is propagaged in air.

The K mirror assembly in application is mounted in a housing, which is in turn mounted on a ball bearing structure so that the prism assembly may be smoothly rotated about the optical axis. Rotation of the prism structure causes the image transmitted through the structure to rotate at a rate which is equal to twice the rate of rotation of the assembly.

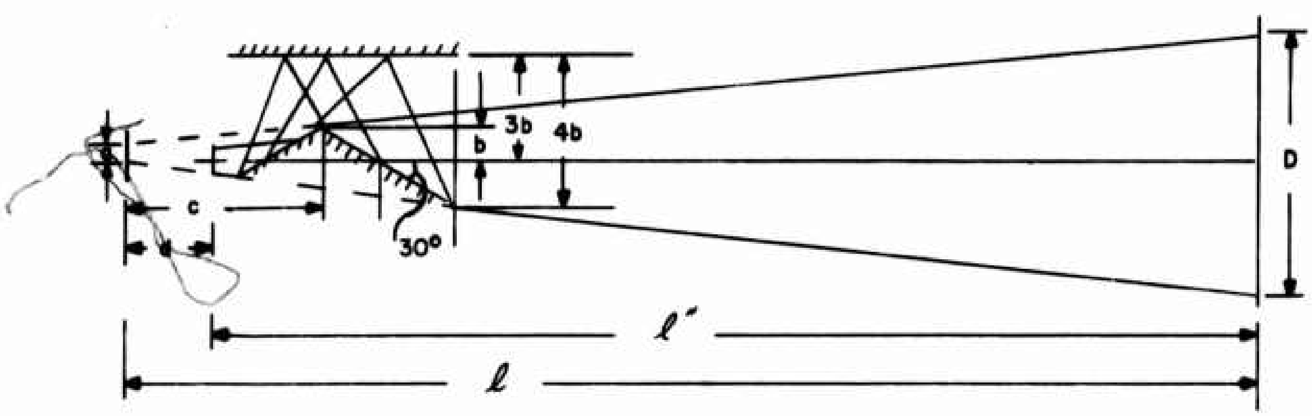
The K-mirror assembly may be replaced by the reversion prism structure shown in Fig. 27a. This prism behaves exactly as the K-mirror assembly. Here, however, the optical signal is propagated through the glass and is acted upon by a total internal reflection from the prism surfaces rather than reflection from metalized surfaces. As with the K-mirrors, the prism may be used in either collimated or uncollimated light, and rotation of the prism about its optical axis produces rotation of the image at twice the rate of rotation of the prism.

Since the optical signal is propagated through glass rather than air, the divergence of the optical signal is not as great in a given length as the signal passing through the prism, resulting in a reduction of the effective path length of the prism and a proportional reduction in the physical size of the optical structure.

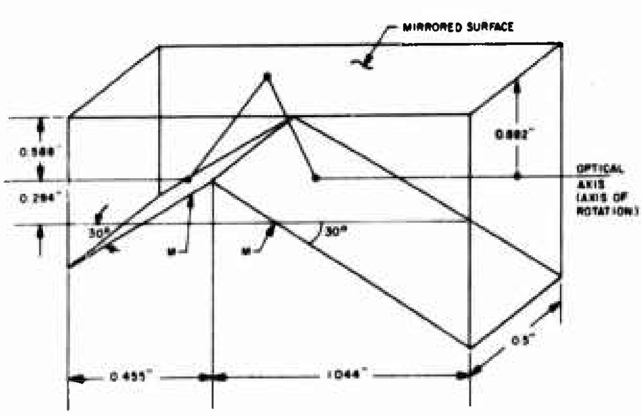
Both the K-mirrors and the reversion prism produce a reverted or mirror image; that is, the image has an apparent left to right inversion as shown in Figs. 26a and 27a. This requires that in the moving map application the holograms be made as reverted or mirror images. This is easily accomplished by reversing the



a. REVERSION EFFECT



b. GEOMETRY



c. CONFIGURATION FOR LABORATORY MODEL

Fig. 26. K mirror.

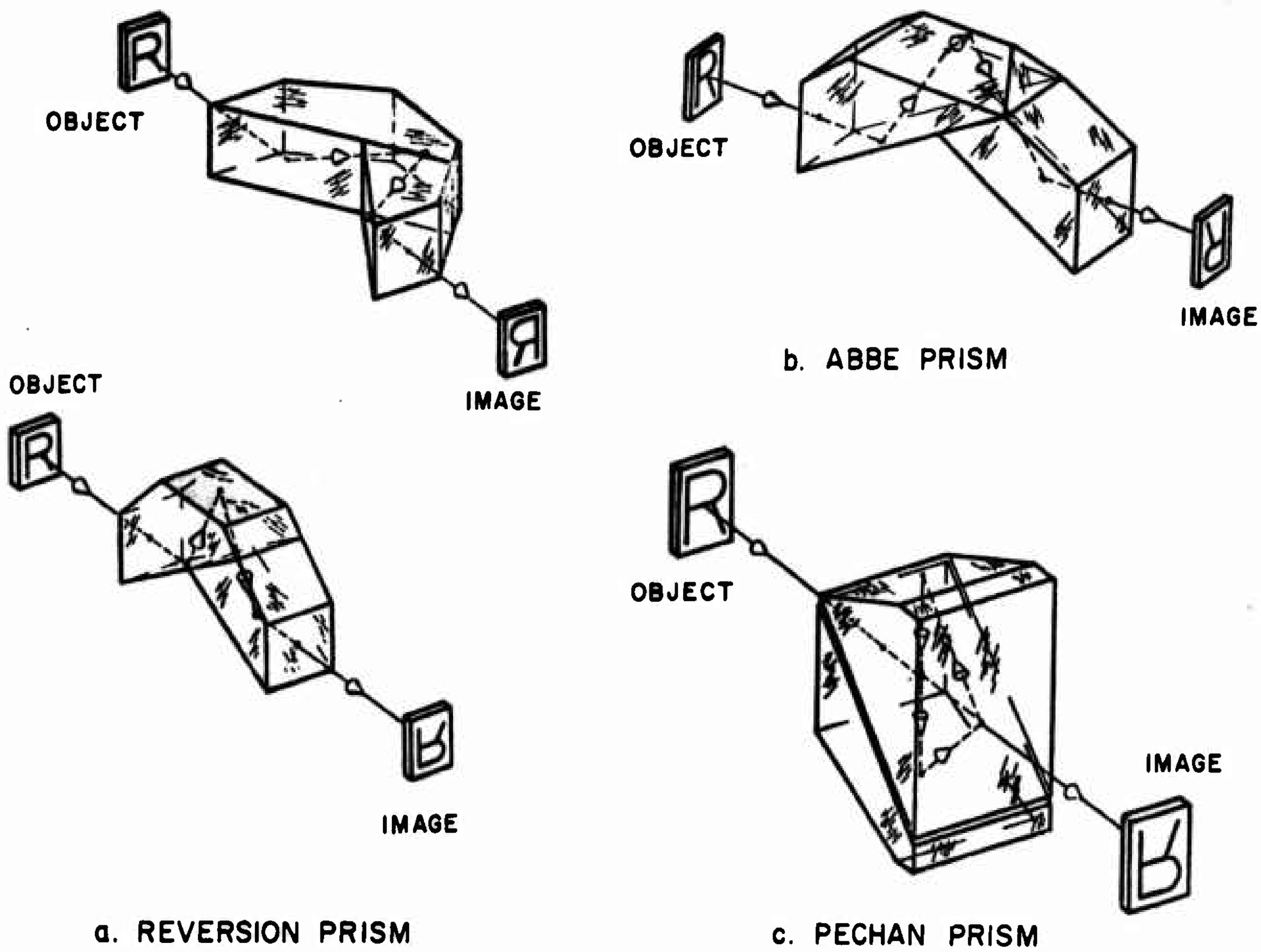


Fig. 27. Rotating prisms.

transparencies when making the holograms and constructing an X-Y translation system such that it takes into account the reverted image.

If as may be the case for some applications, it is desired to record the holograms such that they may be read out with or without the rotation element in place, the reversion prism (or K mirror) must be modified. The addition of a roof to the reversion prism, as indicated in Fig. 27b, will produce a true image. This prism is the Abbe prism; this structure is slightly more complex than the reversion prism and is not recommended unless image reversion cannot be tolerated.

Another prism which can also be used is the Pechan prism shown in Fig. 27c. This prism is more compact and is shorter than the reversion prism.

RCA recommends that the modified reversion prism mounted in a rotating cylinder be used to rotate the displayed image. An outer gear mechanism, shown

in Fig. 28, is coupled either to a direct mechanical drive on a servo control motor to produce image rotation.

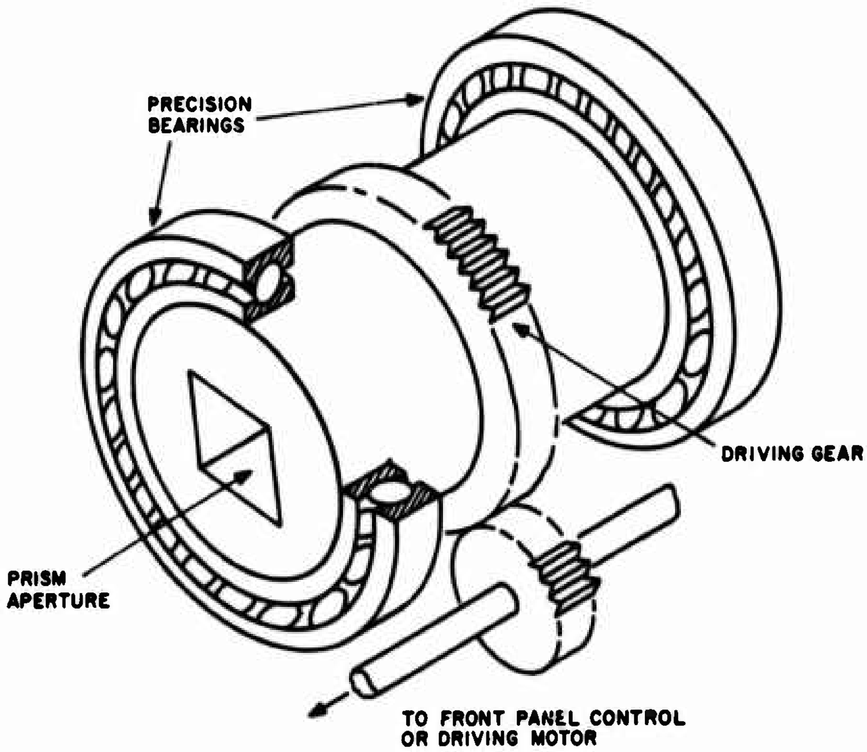


Fig. 28. Rotating-prism mount.

G. SYMBOLOGY

The ability to superimpose various symbols on the moving map display is essential if the display is to be used to its fullest potential. The symbols can be entered on the charts in either of two ways: The symbols can be positioned and can be moved by the pilot (or under the control of a digital memory) while in flight, or the symbols can be entered on the storage medium before flight.

1. In-Flight Character Insertion

a. Systems Considered

Consider first the calling up and positioning of symbols while in flight. A variety of systems have been considered for the application. Two general types are discussed here; the first is a character mask projection system employing multiple galvanometer deflection systems to position characters on the display. To effectively

employ the gain of the directional viewing screen, the character projection system is deflected by means of a pellicle inserted in the main map projection optical system so that the character projection and map projection systems are coaxial. Based on the results of this study, this type of system is recommended for inclusion in future models. It is, however, recommended that this investigation of the techniques of display symbols in flight be extended before defining the system to be used in the prototype system.

The second system replaces the character mask with projection kinescope; however, with the constraints placed on the systems by the map projection optics, this method is considered to be impractical.

Several holographic systems were also considered. At present all of these systems possess severe technical limitations.

b. Character Insertion Projection Systems

Consider projection insertion of the characters on the display first. Such a system would have to display as a minimum, three symbols (e.g., +, 0, □) which can be independently positioned and which move and rotate as the displayed map moves and is rotated.

A projection system employs multiple galvanometer deflection systems capable of performing the in-flight notation function as shown, in Fig. 29. In this system a single high intensity source is used to illuminate three character masks. A condenser lens is employed to increase the collection efficiency of the optical system by imaging the point source as masked by the character mask to the center of the imaging lens. The imaging lens images the character on the viewing screen. The imaging cone is reflected from two mirrors (mounted on rotating galvanometers), which deflect the beam in X and Y directions, passed through a beam combination prism, and reflected down the optical axis of the main projection system by means of a pellicle. The reflected signal passes through the same rotating prism to form a properly registered symbol on the display.

The system, as shown in Fig. 29, is capable of projecting and controlling the position of four characters simulataneously. Reduction of the number of characters required, however, increases the optical efficiency of the projection system.

The pellicle is an essential component of the system (in practice a prism may be inserted in place of the pellicle, if the extra mechanical strength that the prism offers is required). The insertion of the character information in the optical path be means of a reflective element in the manner shown makes the character information appear as if it is derived from an on-axis projection system. This is required, as a result of the inclusion of a direction viewing screen at the system output. The pellicle

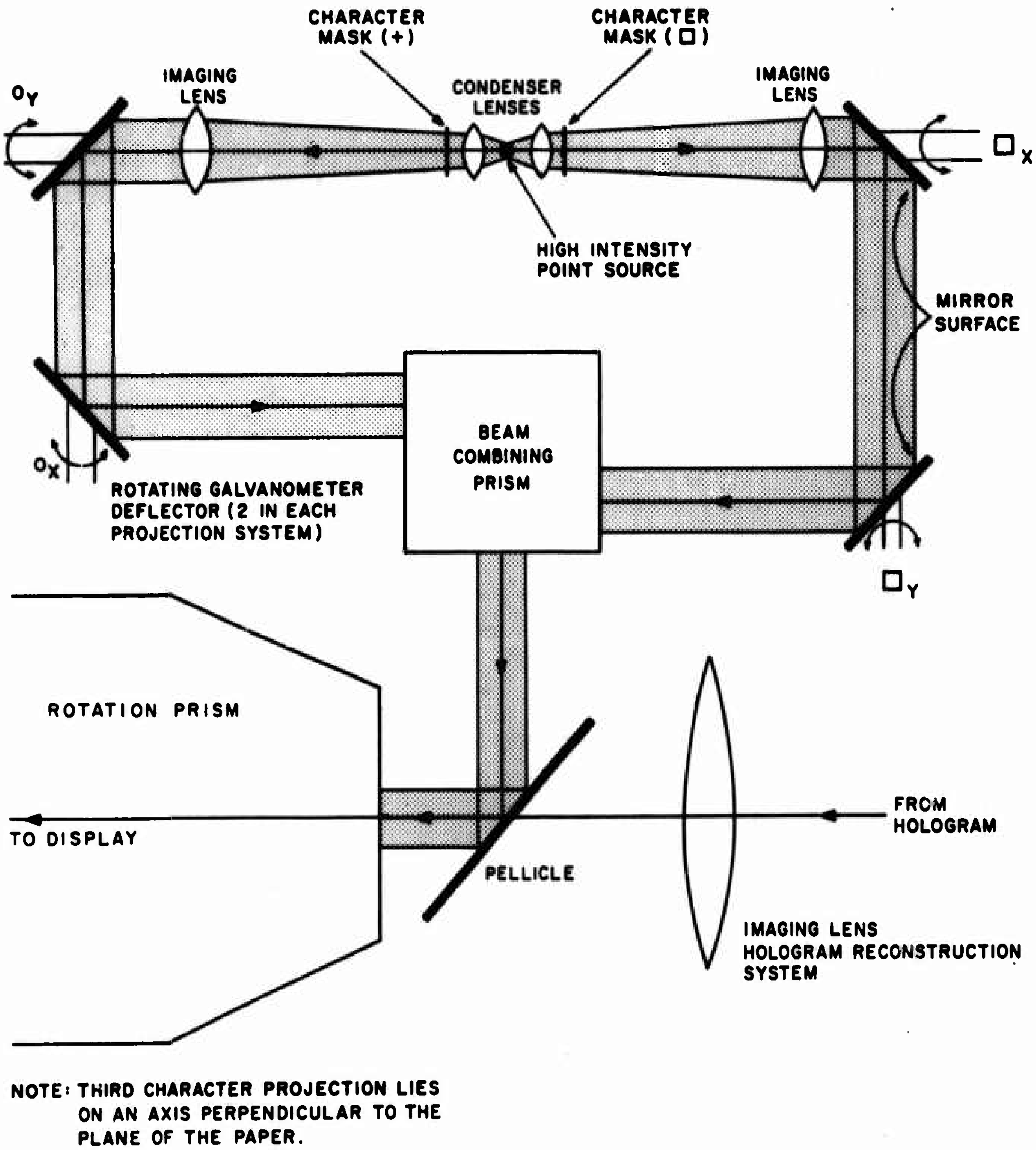


Fig. 29. Projection character insertion system.

is designed so that it will transmit 90 to 92 percent of the energy and reflect 8 to 10 percent. Operated in this mode when the pellicle is inserted, the highlight brightness of the chart information will be reduced by 10%, while 10% of the energy falling on the pellicle from the character projection system is directed toward the viewing screen. This greatly reduces the brightness of the characters as compared to that which can be developed if all of the light developed by the optical project system were directed toward the screen. This energy will be collected with the same screen gain associated with the chart display and will consequently exhibit a character brightness several times that of the highlight map display brightness.

The intensity of the displayed symbols is controlled by adjusting the intensity of the point source. For night viewing a red filter is placed in front of what is normally a white light source.

A diagram indicating the nature of the electronics associated with this method of character insertion is shown in Fig. 30. Here X and Y position information may be inserted by the pilot from the front panel by storing position information in motor driven pots. The pots are in turn summed with information describing the map deflection and then fed to galvanometers to properly position the mirror face to display the character in the desired position.

The system described here is a basic system which applies a brute force approach to provide a rugged and dependable character insertion system. This system can be built reliably with existing techniques.

If, as will be the case in more advanced systems, it is required that the symbol insertion be controllable not only by the pilot from the front panel, but also by a digital input, the motor driven pots are replaced by digital memories and a logic system which assumes a form similar to that indicated in Fig. 31.

In this system a storage register is included for each symbol to be displayed. An address tag indicating the type symbol to be displayed routes the positional information associated with the symbol to a storage register controlling the deflection galvanometers associated with that system. The information stored in the register is passed through a digital-to-analog (D/A) converter. A single 8-stage D/A converter which allows the character to be positioned to 1 part in 250 is associated with each galvanometer.

As before, the characters are made to move, as the chart moves, by the addition of an analog deflection signal to the signal developed at the output of the D/A converter.

The above system can be modified by the use of an X-Y galvanometer such as that constructed by General Scanning Inc., Watertown, Mass. This unit,

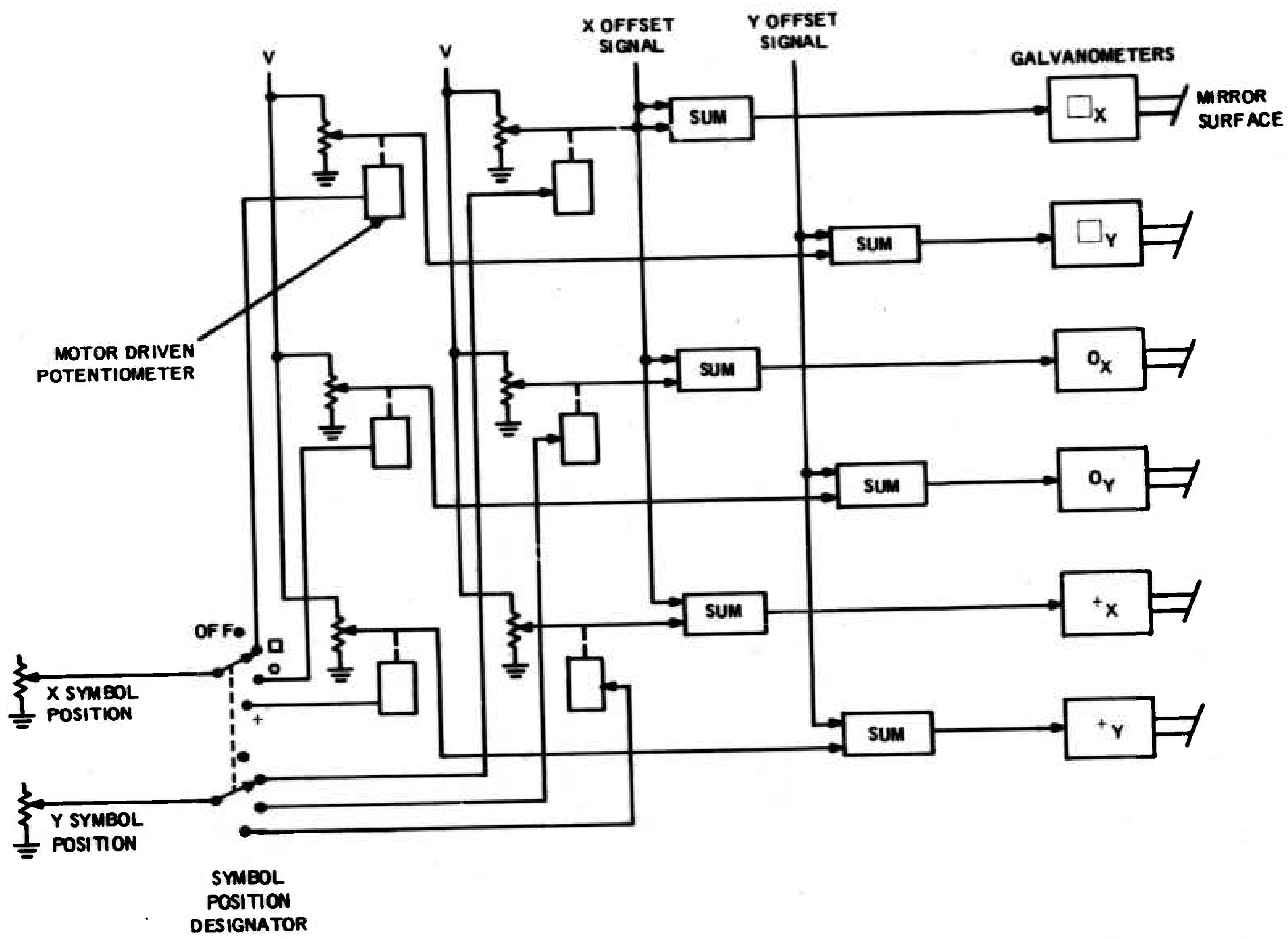


Fig. 30. Projection system analog electronics, block diagram.

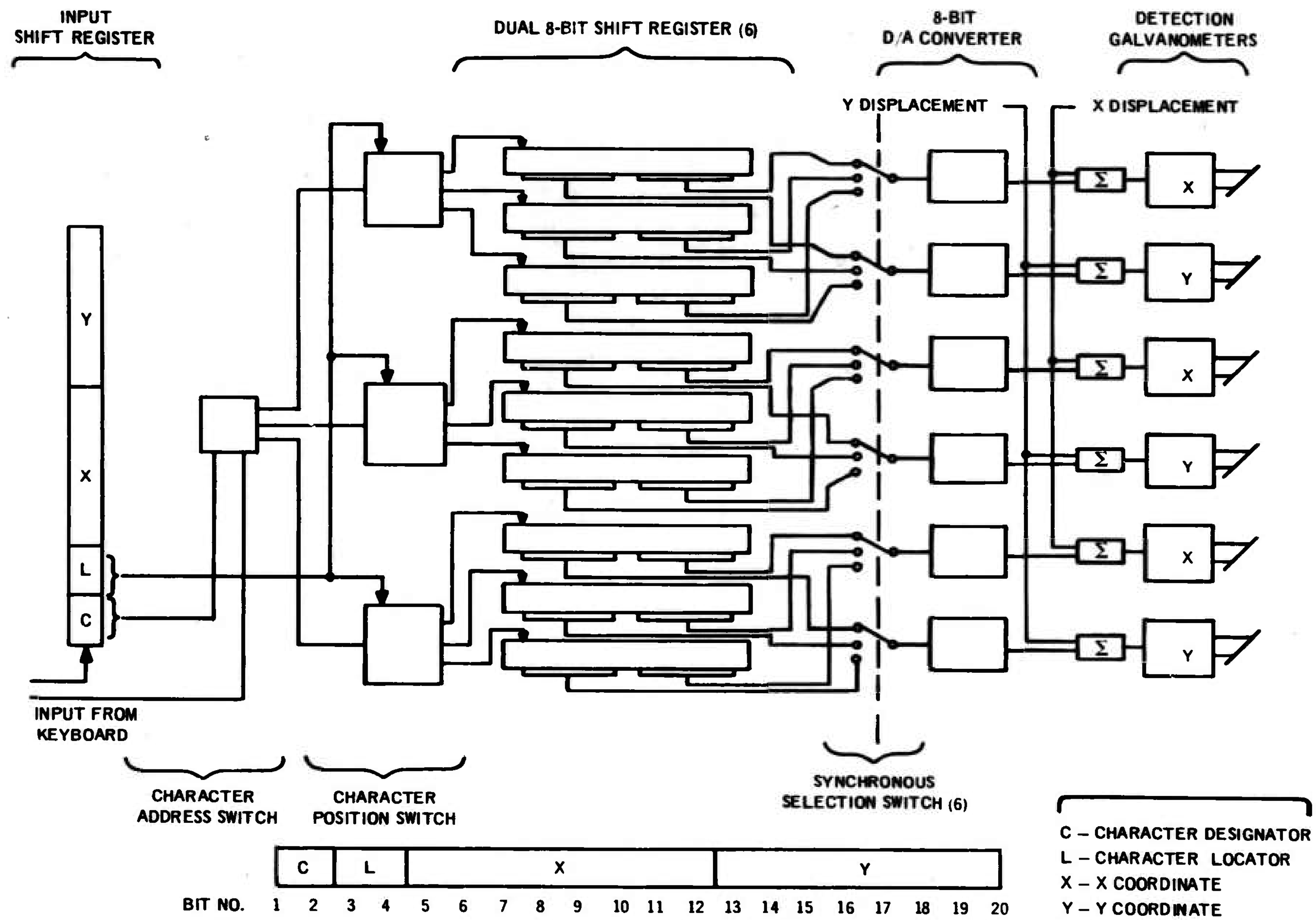


Fig. 31. Projection system digital electronics, block diagram.

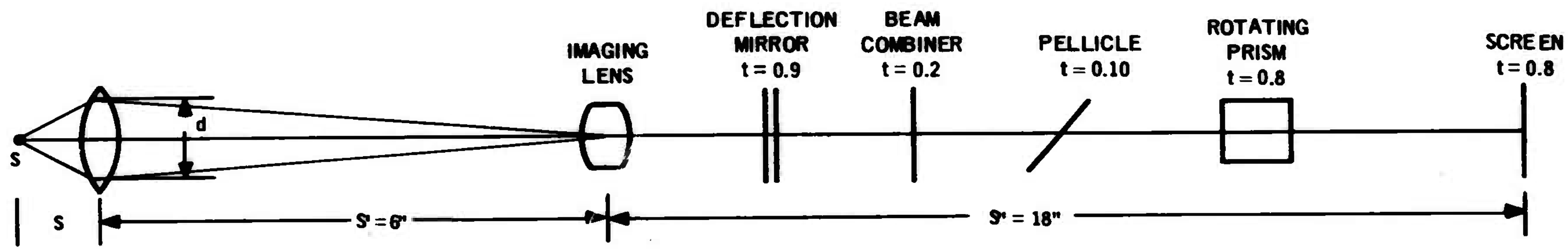
which was designed for use primarily in laser deflection systems, has an 800-Hz bandwidth. The system allows one character be positioned at several locations on the display by deflecting the galvanometers at a rate which is higher than the flicker rate of the eye. In this fashion the system offers the possibility of displaying as many as four characters in each of three positions on the display for a total of 12 position designations. This system can be further modified by removing one of the character masks and imaging the point source directly to the viewing screen. Deflection electrons can then be utilized allowing a line (or perhaps lines) to be drawn on the display using a vector generator controlled by the pilot. This feature then would allow the insertion of as many as 9 characters plus a line vector.

1) Systems I and II Photometry

Both the above optical systems can be analyzed by assuming the optical schematic shown in Fig. 32. The flux density, transmitted through the viewing screen, B_V, is defined by Eq. (3), Fig. 32. The source is assumed to be a point source for the analysis and radiates isotropically. The flux radiated by the source is described by Eq. (4), Fig. 32. As shown by the analysis a flux density at the display of approximately 82 lumens/sq. ft. is developed if it is assumed that a 150-watt source radiating with emissivity of 0.03 and producing 400 lumens/radiated watt is used as the power source. This is 4 to 5 times the flux density developed by the display. Therefore, the apparent brightness of the character would be 4 to 5 times that of the highlight area of the aerial chart. Multiple character displays from a single character projection channel; i.e., by deflecting the galvanometer system at a high rate with respect to the flicker rate accommodated by the eye, will reduce the apparent brightness by the number of characters displayed. The display of three characters from a common system will result in a displayed character having a highlight brightness equivalent to the highlight brightness of the display.

2) System III Photometry

An alternate method of inserting symbols by means of a kinescope projection system was evaluated and rejected as being impractical. In this system a kinescope is employed in conjunction as the character source. Characters are formed on the face of the kinescope either by means of a digitally controlled character generation which operates on the deflection system to write a character on the CRT face or by scanning a small character size raster and blanking the tube in conjunction with information derived from a "Characertron". As postulated, characters would be formed in succession on the face plate and would be directed to the proper position on the viewing screen by a single galvanometer deflection system. The control electronics for the galvanometer system is similar to that proposed earlier. If a deflection system having an 800-Hz bandwidth were employed, six to ten characters could simultaneously be displayed on the screen.



B_V = HIGHLIGHT FLUX DENSITY ON VIEWING SCREEN
F_S = FLUX RADIATED BY THE SOURCE INTO 2π STERADIANS
= $Pe\eta$
P = LAMP POWER
e = EMISSIVITY OF TUNGSTEN AT 2780°K = 0.03
η = CONVERSION EFFICIENCY LUMENS/RADIATED WATT
ℓ = FOCAL LENGTH OF CONDENSER LENS
m = MAGNIFICATION S"/S'
E_m = FLUX DENSITY AT CHARACTER MASK LUMENS/WATT

$$[1]\quad E_m = \frac{\pi}{4}\left(\frac{2\tan^{-1}\frac{d}{2S}}{2\pi}\right)^2 \frac{F_S}{\pi\left(\frac{d}{2}\right)^2}$$

REDUCING AND EXPRESSING S IN TERMS OF S' and ℓ

$$[2]\quad E_m = \left[\frac{\tan^{-1}\frac{d(S'-\ell')}{2S'\ell}}{\pi}\right]^2 \frac{F_s}{d^2}$$

THE BRIGHTNESS AT THE VIEWING SCREEN BECOMES

$$[3]\quad B_V = \left[\frac{\tan^{-1}\frac{d(S'-\ell')}{S'\ell}}{\pi}\right]^2 \frac{F_S}{d^2m^2}\, t_m t_{BC} t_{pel} t_{SC}$$

ASSUMING

P = 150 WATTS
d = 0.028 FT
S' = 0.5 FT
ℓ = .028 ft
m = 3
t_j – AS SHOWN

AND SUBSTITUTING INTO [3]

B_V = 82 LUMENS/SQ. FT.

Fig. 32. Deflection optical schematic for systems I and II.

This system although appearing attractive at first glance is not. The limit is imposed by the optics required to produce the moving map having sufficient brightness to be compatible with the requirement that it could be used in an aircraft cockpit. The constraints are introduced by two factors: First, to produce a display having the required apparent brightness, a rear-projection, highly directional screen is employed. The use of this screen requires that the character insertion system appear to be on the same optical axis as the chart projection system. This implies, if the optical losses are to be held to a minimum, that the character projection system pass through the same rotational element required to rotate the map. The analysis, associated with Fig. 33, shows that if the optimum optical system is used for the map projection system, the effective f/number of the character insertion system is of the order of 35. Operation at that f/number is prohibitive requiring impractical beam current and power densities in the kinescope.

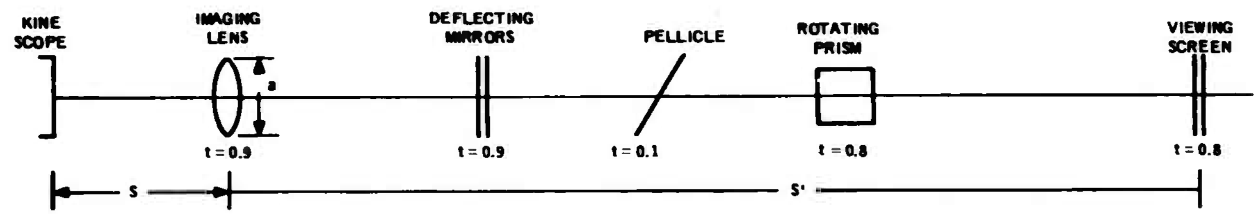
The f/number restriction may be eased by increasing the size of the aperture of the rotational optical element. A simple calculation shows, however, that the element becomes prohibitively large before the brightness of the display approaches an acceptable level.

2. Pre-Flight Map Annotation

Pre-flight annotation of aerial chart information may be accomplished by storing holograms of the symbols to be displayed on the same area as the holographic representation of the aerial chart. This is most readily accomplished by embossing the symbol information over the previously embossed map information in the proper position to properly register the symbol on the display. As with the chart information, the rotation information is stored using focused image holograms. An unlimited number of symbols to be presented simultaneously can be recorded in this fashion.

As with the storage of chart information, the holographic representation of the symbol would be stored on a nickel master, which in turn is mounted on the platen of a precision keyboard addressed typewriter. In operation, an operator inserts the cassette containing the map to be annotated in a display unit. He then displays the map and positions it such that the point at which the symbol is to be inserted lies directly under a reticle on the viewing screen. The proper key is then pushed on the keyboard to activate a precision punch mechanism which embosses the holographic information necessary to reconstruct the symbol designated by the selected key in the proper position on the holographic storage medium.

The system, as described above, implies operation by an operator. The same basic technique could be employed in an automatic digitally controlled access, registration and embossing system. A map selection and registration system identical to that proposed for map selection in the display unit could be used to position the film



DETERMINE CURRENT DENSITY IN KINESCOPE NECESSARY TO PRODUCE A DISPLAY OF ACCEPTABLE BRIGHTNESS

ANALYSIS

[1] $J = \frac{I_b}{nA_K}$

- J = FACE PLATE CURRENT DENSITY, A/CM^2
- n = NUMBER OF CHARACTERS DISPLAYED
- A_K = ACTIVE FACE PLATE AREA/CHARACTER
- I_b = BEAM CURRENT

[2] $\bar{P} = JV$

- $\bar{P}$ = FACE PLATE POWER DENSITY, $WATT/CM^2$
- V = ACCELERATION VOLTAGE, VOLTS

[3] $I_b = f(B_{VS})$

AS FOLLOWS

$$B_{VS} = \frac{B_K T_{SYS}}{4 f_\infty^2 (1+m)^2}$$

- B_{VS} = FLUX DENSIYT OF VIEWING SCREEN/CHAR LUMENS/SQ. FT.
- B_K = BRIGHTNESS OF KINESCOPE, LUMENS/SQ. FT.
- T_{SYS} = SYSTEM TRANSMISSION
- m = MAGNIFICATION KINE TO SCREEN
- f_∞ = INFINITY F/NUMBER AT THE IMAGING LENS.

[4] BUT $B_K = \frac{F}{A_K}$

F = RADIATED FLUX

AND

[5] $F = V I_b \eta \xi$

η = PHOSPHOR EFFICIENCY (RADIATED WATTS/WATT)

ξ = LUMENOUS EFFICIENCY (LUMENS/RADIATED WATTS

[6] OR $I_b = \frac{4 f_\infty^2 (1+m)^2 A_K B_{VS}}{V \eta \xi T_{SYS}}$

$$= \frac{4 f_{eff}^2 A_K B_{VS}}{V_\eta \xi T_{SYS}}$$

ASSUME a/S' OF PROJECTION SYSTEM MATCHES THAT OF THE HOLOGRAM RESTORATION

ASSUMING $a = 0.5''$, $S'' = 18''$, $S = 4.5''$

(ie $m = 4$)

$f_{eff} = 3.6$

ALSO ASSUMING

$A_K = \left(\frac{0.25}{4}\right)^2$ SQ. INCHES

$V = 30$ KV

$\left.\begin{array}{l}\eta = 0.14 \\ \xi = 480\end{array}\right\}$ P-20

$T_{SYS} = .052$

$I_b = 12.2 \times 10^{-5} B_{VS}$ AMPS

ASSUME $B_{VS} = 50$ LUMEN/SQ. FT.

THEN $I_b = 6.1$ MA/CHAR

THIS CURRENT DENSITY IS SEVERAL ORDERS OF MAGNITUDE TOO HIGH TO BE EFFECTIVE.

Fig. 33. Deflection optical schematic for system III.

in the embossing unit. However, the inserted digital positioning information indicates the position of the character to be inserted. Once the film is positioned, the character is automatically embossed. Operation in this fashion allows the completely automatic pre-flight annotation which can be implemented to run under the control of a digitally stored memory.

Section V

SYSTEM UTILIZATION

The previous sections have described a variety of techniques which in combination define a practical system for storing and displaying multicolor information to a pilot in a cockpit environment. This section is concerned with several aspects for utilization of the developed techniques and the defined system. These aspects include first the generation of large volumes of holographic material and second the means of using this material in conjunction with the holographic display.

The system, presented in Sections III and IV, employs a hologram photoresist master to produce a nickel embossing master which in turn is used to produce vinyl copies. Three color separations of an aerial chart are holographically recorded on a common photoresist area, along with indexing information. This information is recorded with a reduction in size of the order of 25 to 1. The generation of the original hologram master is an exacting process and will probably have to be produced in a controlled environment. In one implementation of this process, three color separations of the information to be displayed are generated by photographing a full-color original through three color-separation filters. The color separations are generated so that at a later time they may be precisely registered. These color separations are used to generate the photoresist hologram. The holographic exposure must, with present technology, be performed in a low-vibration environment. Once the photoresist master has been generated, an original nickel copy may be produced from which second-generation nickle copies may be produced for distribution to all (perhaps thousands) user stations (aircraft carriers, airports, etc.). It is this second-generation nickel copy which is used in the field to generate vinyl copies which are used in the cockpit display unit. In the configuration recommended, a 12.5-in. (18-in. diagonal) chart segment along with its data block information is stored in each generated hologram.

A requirement exist that 500 such aerial charts along with checkout lists, flight plan information, etc., be made available to the pilot either under his direct control or under the control of a digital signal. Access to a particular frame of the 500 charts should occur in less than 3 to 5 seconds. The time to move from one frame to the next frame in sequence should be of the order of 100 milliseconds. Access from one frame to a frame 30 frames away (the typical case for area coverage when flying in a direction perpendicular to the direction in which the maps are sequenced) should occur in the order of 300 or 400 milliseconds. To perform this function RCA recommends that the information be stored serially on reeled vinyl tape in a cassette. The cassette should be designed such that it can be quickly inserted and removed from the unit while in flight. Therefore, the pilot has the capability of accessing a virtually unlimited data base by changing cassettes.

A flow chart for the generation of vinyl strip of maps in a sequence designated by a mission compiler is shown in Fig. 34. The mission compiler which may be operated under the control of a man, a digital program, or both would select the maps to be recorded in accordance with some prescribed criteria (the sequence in which they would be used, area coverage, format, etc.). Using this technique, charts of different types and scales as well as other types of prerecorded information required by the pilot can be mixed on a common cassette.

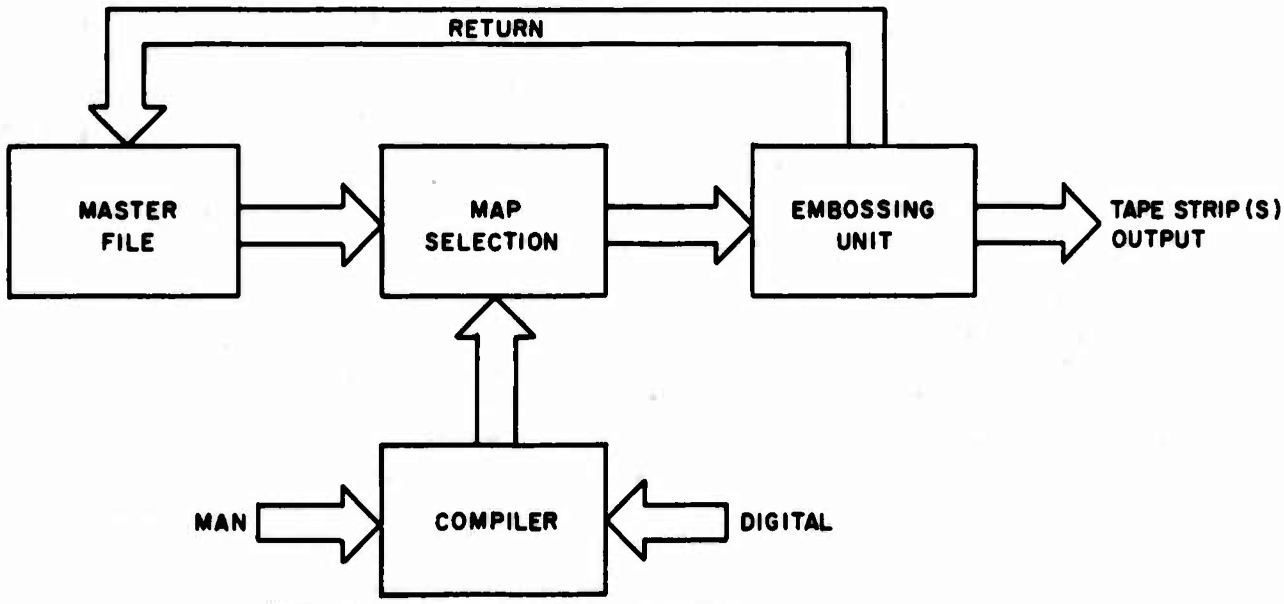


Fig. 34. Sequence for assembling map strips.

Once the sequence of frames desired has been designated, a map selection unit is addressed which extracts the information from a master file in the proper sequence. The information stored in the master file is the second generation hologram nickel master, which is used to emboss the vinyl tape. Each information frame (a holographically stored aerial chart or other instructional information) is stored on a nickel chip which is precisely mounted on a precision registration card. The map selection unit transfers the extracted card to an embossing unit. The embossing unit transfers the relief image stored on the nickel master to the vinyl tape by a hot stamping process, at the location specified by the compiler. If multiple reels are to be generated, this card is transferred to a second embossing station and a second tape embossed. This process is repeated as many times as is required to generate the desired number of tapes. After the desired number of tapes have been generated, the chip is returned to the master file.

Preliminary consideration of the nature of the embossing unit has led to the conclusion that a unit could be constructed which has a volume equivalent to two standard office desks stacked one on top of another. This unit would be capable of storing the masters and embossing as many as 500 map reels in under 45 minutes. The unit could be mounted in a van or aboard a ship.

For the holographic configuration recommended in Sections III and IV, upwards of 10,000 aerial chart segments having an 18 inch diameter (or a square 14.5 inches on a side) could be stored in a 3/4- by 3-1/2- by 7-in. cassette; five hundred aerial charts could be stored in a 3/4- by 2.5- by 3.5-in. cassette. Both the cassette and the recording material are inexpensive (estimated to be under one dollar when produced to military specifications). At the completion of the mission the tape may be thrown away; the cassette can be reused.

Section VI

DESCRIPTION OF LABORATORY SETUP

During the course of this program, specialized laboratory equipment has been developed to investigate the tradeoff parameters involved in the construction and reconstruction of full color maps. An over-view of the laboratory recording setup is shown in Fig. 35. The optical paths and the recording fixtures at the holographic plane are shown in Figs. 36 and 37, respectively. As previously discussed, a quasi-focused image hologram is formed by constructing a defocused image of the object in the recording plane and interfering that image with a spherical reference beam. The resultant interference pattern is recorded on a photosensitive material to form the hologram.

The 4416Å line of a helium-cadmium laser is gated by an electronic shutter (Fig. 36), used to control exposure time, and is then deflected by the first of four folding mirrors, M_1. The collimated beam is then divided into two components by a variable ratio beam splitter. The component of the beam that passes through the splitter strikes folding mirror M_2 and is then focused to a spot by lens L_1, on a pin hole P_1. The combination of lens L_1 and pinhole P_1 form an optical low-pass filter that eliminates non-uniformities introduced in the beam prior to this point. The divergent light, effectively originating from a point at P_1, is allowed to expand to a diameter large enough to evenly illuminate the object after it has been recollimated by a larger condenser lens, L_2. The expanded collimated beam is then transmitted through the transparency containing the information to be recorded, modulating the laser beam. The modulated laser beam is collected by a second large condenser lens L_3, and directed at the imaging lens L_4, after reflection by folding mirror M_4.

The imaging lens L_4 is placed at the focal point of L_3 and, as such, received all of the energy that is transmitted through the object. This lens then forms a real image of the object in a plane at or near the holographic recording plane, H. If the holographic plane is in the image plane of lens L_4, a focused image hologram will be recorded. If, however, the holographic plane is displaced from the image plane, a quasi-focused image hologram will result.

A second component of the original beam emitted by the laser is derived by reflection from the splitter and directed by mirror M_3 to the spatial filter formed by lens L_5 and pinhole P_2. Lens L_5 is so positioned as to cause the energy passing through pinhole P_2 to appear to have originated from a point in the principle plane of the imaging lens L_4, and to uniformly illuminate the holographic recording plane, H. The interference pattern formed at H by the two mutually coherent beams of light, one modulated by the object and the other unmodulated, form a hologram.

Fig. 35. Over-view of holographic recording system.

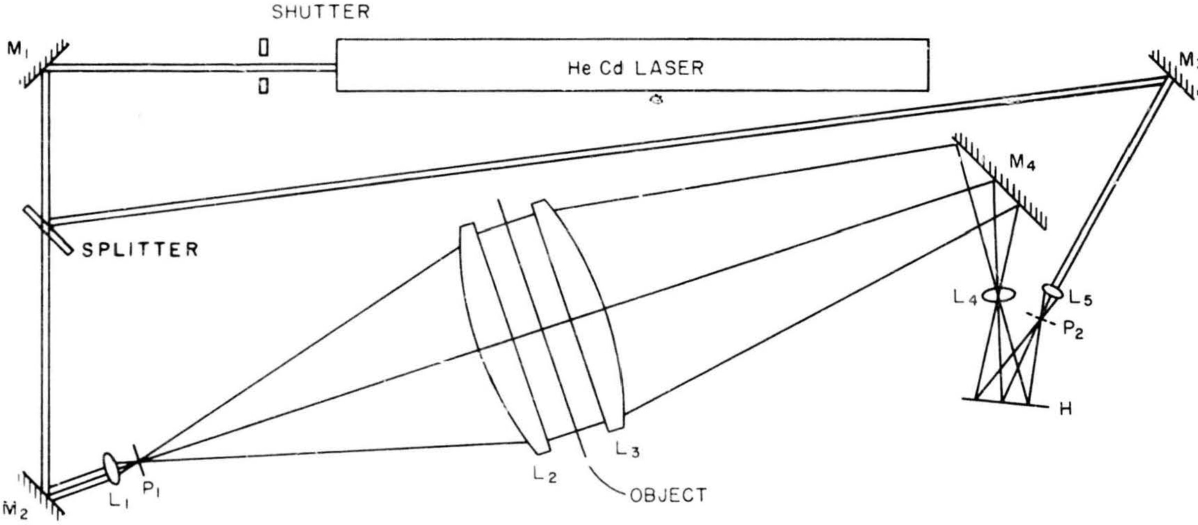


Fig. 36. Quasi-focused image hologram recording schematic.

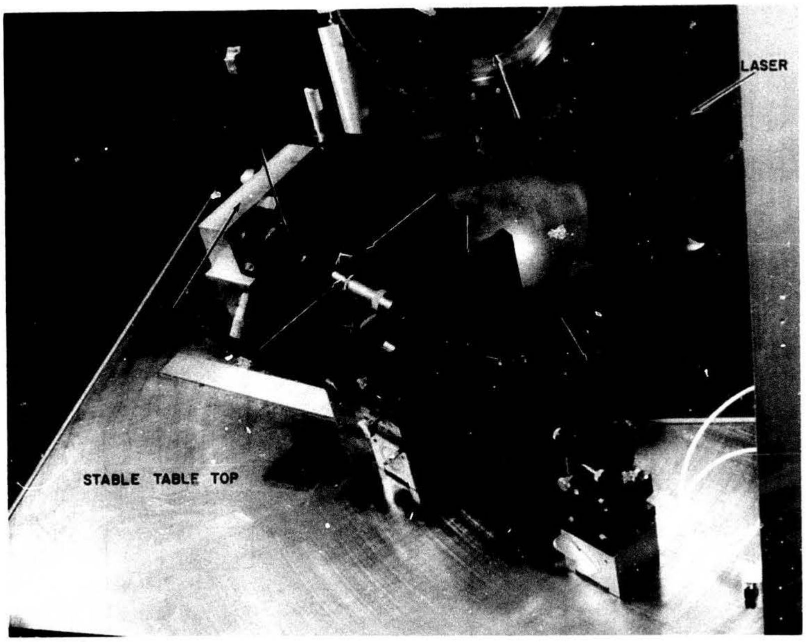


Fig. 37. Holograph recorder, recording area.

A full color hologram is recorded by utilizing a set of three color separations, recorded individually, on a common area of the hologram. The meridional reference beam angle is, however, changed between each exposure. The technique is described in detail in Section III.

After the holographic plate is processed, a full color image can be restored using the readout (or reconstruction) system shown in Figs. 38 and 39, for reconstruction by filtered white light in a reflection mode. In this configuration the light from three xenon arc sources is reflected by three steering mirrors (M_5, M_6, and M_7) to three separate blazed reflective gratings, G_1, G_2, and G_3. These gratings disperse the white light by an amount exactly equal to the chromatic dispersion of the hologram but opposite in sense. The chromatic dispersion of each of these elements exactly cancel each other such that no dispersion exists in the image plane. Lenses L_7, L_8, and L_9 shape the wavefront of the restoration beams to match that of the recording beam. Lens L_6, directly ahead of the hologram, collects the light diffracted by the hologram and focuses it on the imaging lens, L_4.

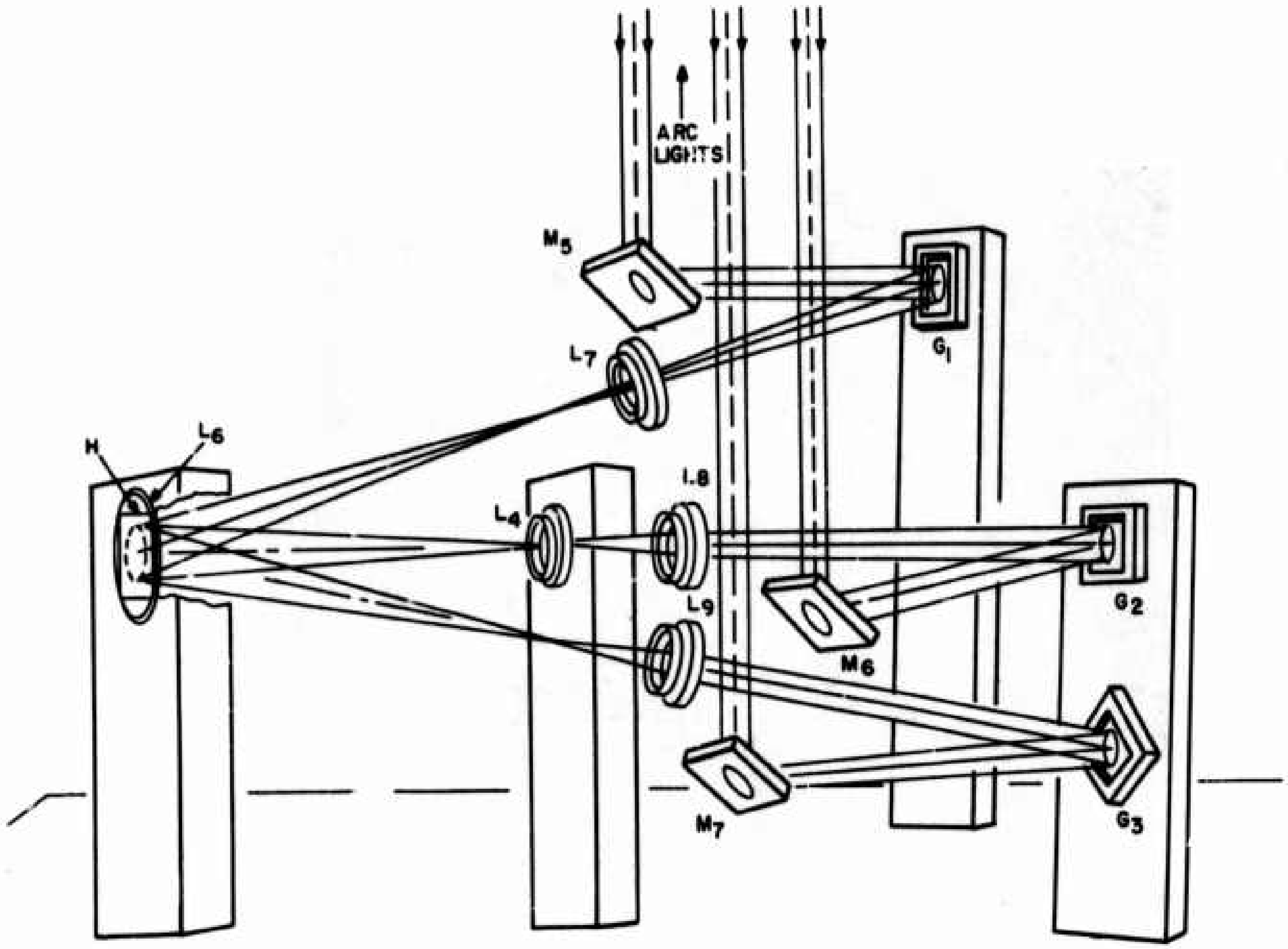


Fig. 38. White-light readout-system, schematic.

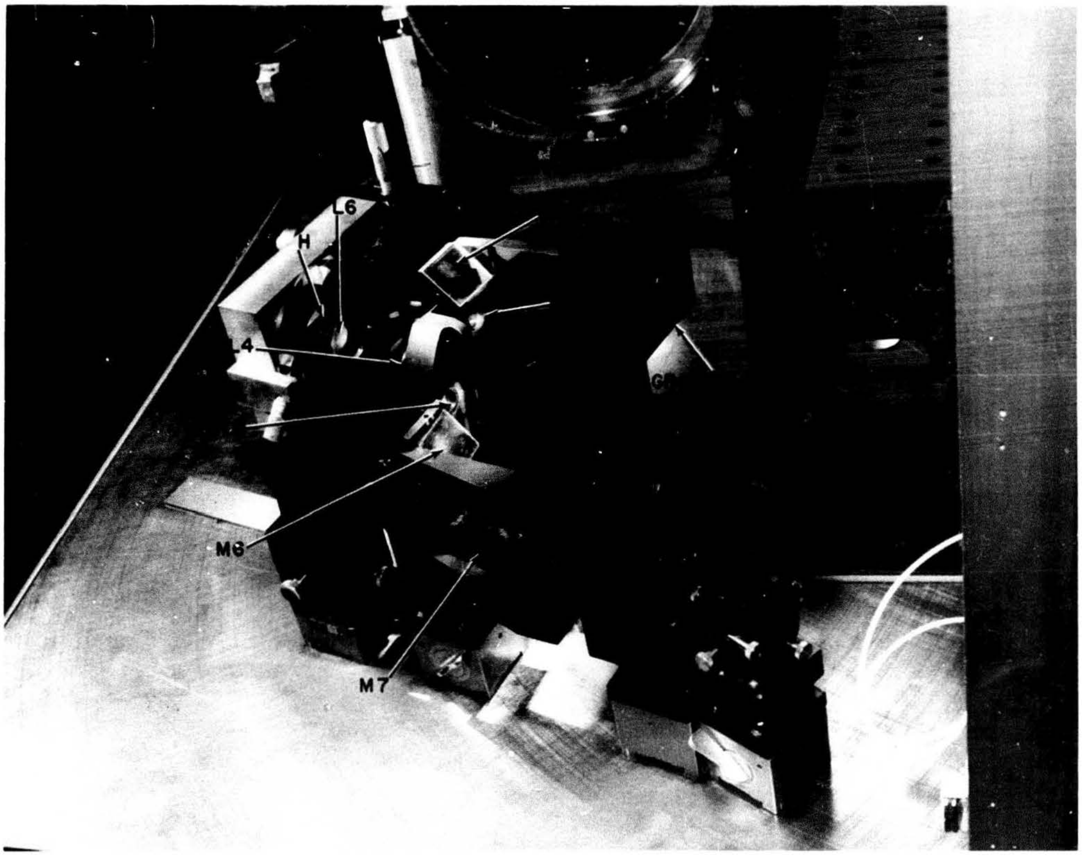


Fig. 39. Reconstruction system laboratory setup.

Section VII

CONCLUSIONS AND RECOMMENDATIONS

1. Having completed this study, it is RCA belief that a holographic storage system employing three quasi-focused image holograms to store the necessary information to provide a full-color moving map display of aerial charts offers advantages not found in competing display techniques. The development of such a system to fullfill the Navy's need for the display navigational information in an aircraft cockpit is at this time feasible.

2. Holographic storage of the map information is recommended because of the following associated advantages:

   (1) Inexpensive duplication

   (2) Multiple-image storage (multiple images can be stored on a common holographic area allowing reconstruction of the full color image)

   (3) Stationary image restoration (a holographic data block, which can be used to designate the map) can be recorded over map information. The data block information, upon interrogation, forms a stationary image in space for register on a diode interrogation array.

   (4) Non-absorptive storage media (large amounts of optical power can be gated resulting in a bright display from a high density storage media)

   (5) Large depth of focus.

3. The multi-exposure quasi-focused image technique using white light sources for reconstruction is selected as the optimum technique for recording the multicolor moving map information for display in a cockpit.

4. A direct view display using white light sources is recommended as the optimum method of displaying the reconstructed information. Color television displays were investigated and were found to be impractical for the aircraft cockpit color display application. The primary limitation was in the brightness of the display that could be developed in the cockpit.

5. The Fraunhofer hologram with its associated stationary image characteristic recorded over the map information is recommended for storing data block information for use in a rapid retrieval system.

6. The advantages associated with photoresist as compared to other recording material when coupled with the fact the required exposure levels are well within acceptable, practical levels has lead RCA to recommend that this material be used for the multicolor moving map display of information. Shipley type AZ 1350 photoresist is recommended as the original holographic recording material. This material records information as a relief image on the surface. Recording in this fashion allows inexpensive duplication of holograms using nickel plating techniques to generate master copies, which can in turn be used to generate copies on a highly durable inexpensive vinyl material.

7. A highly efficient anti-reflection-coated lenticular viewing screen is recommended as the output element of the display system. In the configuration defined for a recommended laboratory model, such a screen, when operated in conjunction with the holographic system proposed, produces an illumination in the viewing area of 9.85 lumens/sq. ft.

   This is equivalent to a diffuse surface with a brightness of 985 lumens per square foot assuming the surface is 6 inches in diameter and the viewing distance is 30 inches.

8. A display that has a minimum eye relief area approximately 2-1/2 inches high and 6 inches wide is recommended. This viewing area is developed using a directional viewing screen, which has a high gain in the direction of the observer and a low reflectance consequently enabling the maintenance of a high apparent display constrast.

9. Translation of the image is provided by translating the hologram. Image rotation is accomplished by the insertion of a rotating prism in the optical path used to display the map information.

10. Systems have been devised for inserting symbols on the display. Further investigation is recommended in this area to insure the selection of an optimum technique prior to the construction of a prototype model.

Appendix A

RECOMMENDED DEMONSTRATION MODEL CONFIGURATION AND DEVELOPMENT SPECIFICATION

A. MODEL CONFIGURATION

A recommended configuration for a laboratory display model using the quasi-focused image hologram storage technique with white light reconstruction is presented in Fig. A-1. This configuration is capable of meeting the requirements of the tentative specification presented in Section B of this Appendix.

1. Optical

a. Map Display

The quasi-focused image hologram may be read out using white light sources. For reconstruction as a quasi-focused image hologram, xenon arcs are employed. The energy radiated by the arcs is collected by high-efficiency-collection optical elements and directed to a dispersion grating which deflects the energy to the hologram plane. A collimating lens in front of the hologram plane collimates and (after diffraction from the hologram plane) reforms the wavefront to produce an image on the viewing screen after passing through imaging lens L_2, and lens L_1 which is bonded to the screen. The composite optical element (i.e., L_1 and the viewing screen) provides the maximum brightness for a given eye relief area. Both surfaces of this device are coated so as to minimize degradation of image contrast by reflecting ambient light back toward the observer.

The viewing screen, shown in Fig. A-2, has a 6-in diameter and a small segment at the top opaqued for use as a registration area for the address detector array (about 0.25 in^2). A possible configuration for the front panel controls is shown in Fig. A-2.

The primary colors are separated by the angular position of the readout lamp assemblies; the saturation of the color is determined by the position of a band-width limiting aperture in each lamp path. Aperture adjustments should be provided to allow establishment of the optimum viewing condition.

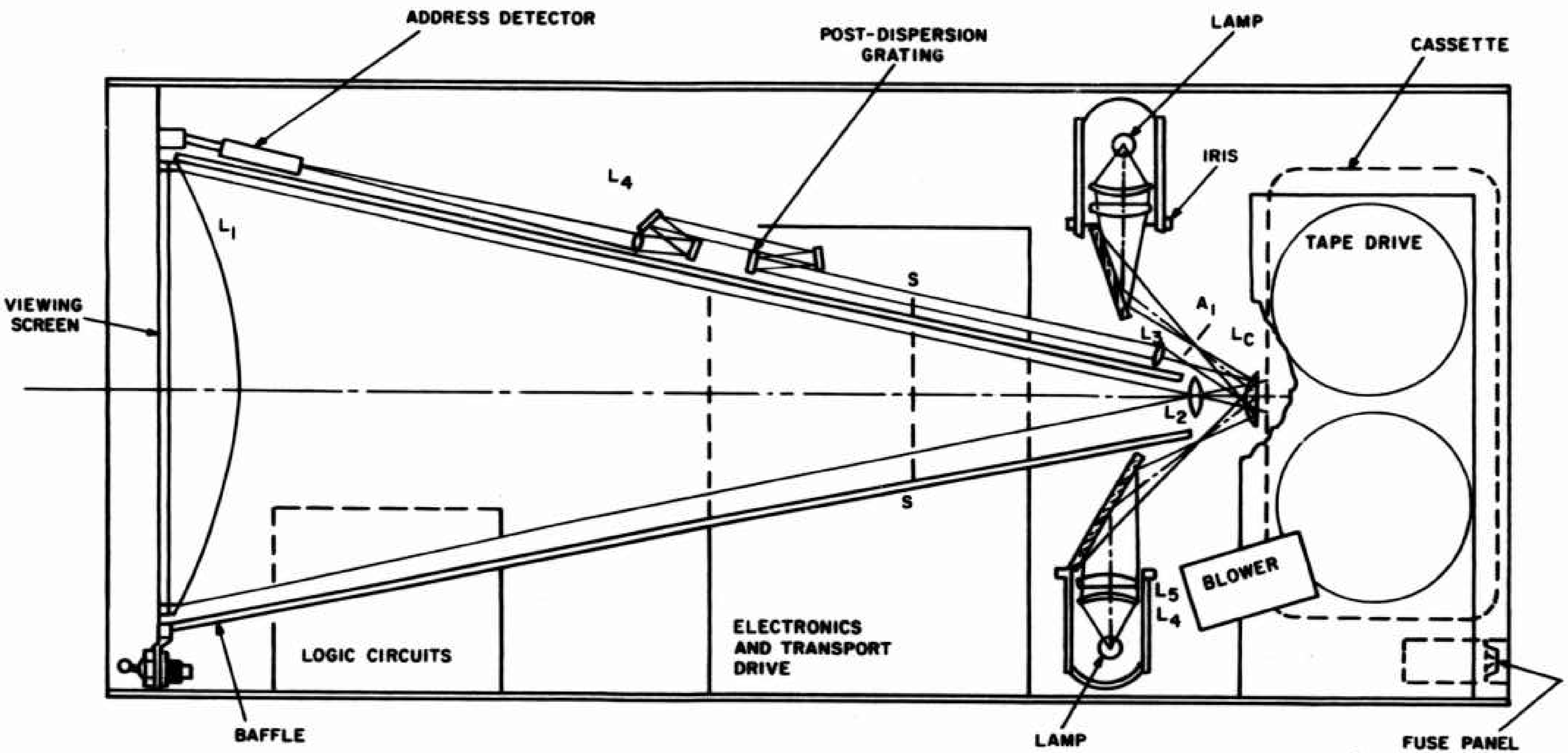


Fig. A-1. Model configuration.

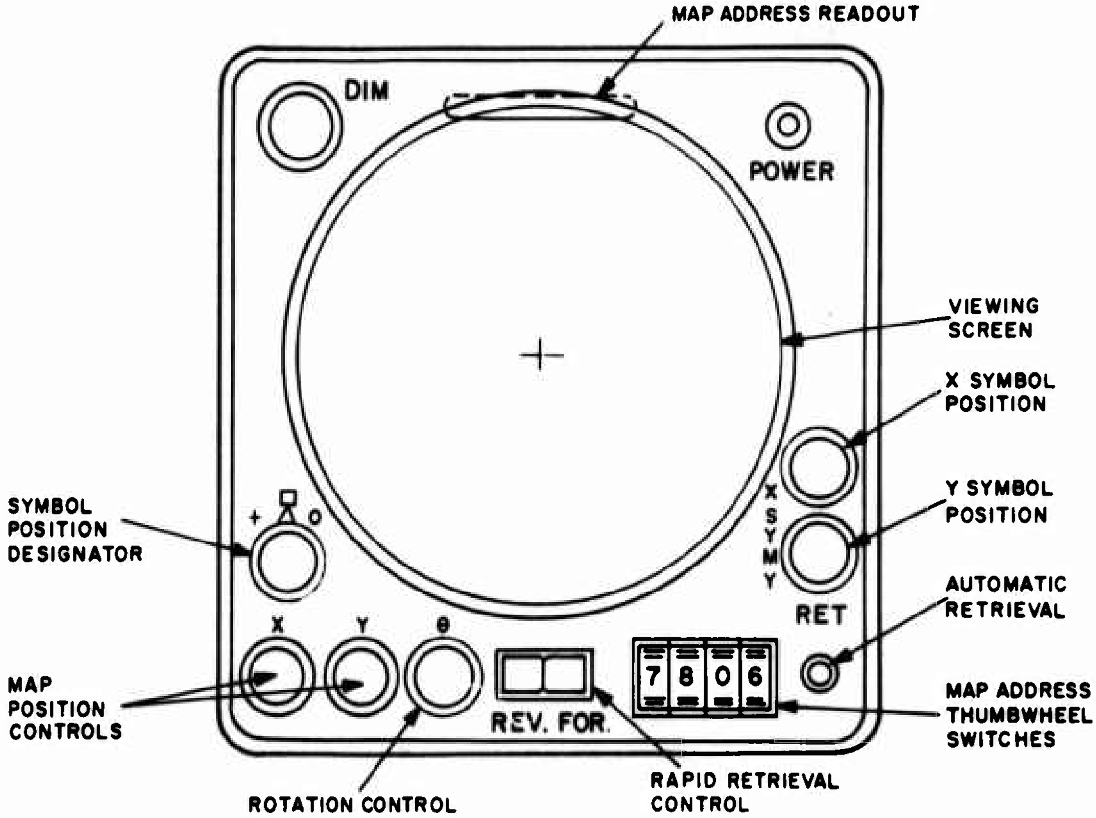


Fig. A-2. Panel configuration.

b. <u>Address Readout</u>

The address portion of the holograms can be read out with one of the three white-light sources used to reconstruct the map portion or an auxiliary GaAs source. The address portion is a Fraunhofer hologram covering the entire map area; it must be read out with coherent light or with incoherent light with some means of correcting the chromatic errors. The method recommended is that of postrefractive dispersion.

The readout beam emerges from a band limiting aperture, A_1 in Fig. A-1, as a diverging beam. The spherical wavefronts of this beam become plane after passing through correction lens L_c. The condition necessary for Fraunhofer readout is now present. After reflection from the hologram, the beam now reenters correction lens L_c. This time, however, lens L_c produces the Fourier transform of the Fraunhofer modulation in the focal plane of lens L_2. This is a real image of the address block. The image is aberrated at this point.

The real image is also in the back focal plane of lens L_3 which collimates light from the real image. The aberrations are now present in the form of collimation angle errors which are a function of wavelength. These errors are corrected by the

insertion of a diffraction grating in the path. The dispersion of the grating and that of the Fraunhofer fringe pattern must be complementary and are made so by using a grating with a spatial frequency equal to that of the average frequency of the hologram.

c. Intensity Control

An observer might wish to use the map display while his eyes are dark-adapted. The brightness of the map image must be reduced in order to meet this condition. The front panel is provided with a dim control for adjusting the brightness to very low levels (Fig. A-2).

Several ways of reducing brightness are available: (1) the power input to the lamps can be varied; (2) the light sources can be adjusted with iris-diaphragm apertures; or (3) a variable neutral density attenuator can be placed in the image optical train.

2. Transport Mechanism

The tape transport system can be designed to allow the holograms to be retrieved in either an automatic retrieval mode, a rapid forward and reverse mode, or a manual mode.

In automatic retrieval, the numerical address of the desired map is entered by setting digital selector thumbwheel switches on the front panel (Fig. A-2). A retrieval button (RET) on the front panel is then pressed to actuate the transport drive which operates until a coincidence is noted between the code set by the operator and that detected by the diode matrix. The tape is then stopped, the motor is shut off, and the hologram storage frame registered to select that portion of the map designated for viewing by the X-Y position controls. In the event of a malfunction, tape limit switches shut off the tape drive near the end of the reel.

Rapid forward and reverse can be activated by a switch on the front panel.

In addition to the tape drive mechanism which changes maps, an X and Y drive should be provided which changes the position of a map image on the screen. This function is manual and can be provided for by separate knobs on the front panel.

3. Image Rotation

Rotation of the displayed image is accomplished by the insertion of a prism in the optical path between the imaging lens and the viewing screen as discussed in Section IV F.

4. Symbology

a. In-Flight Annotation

The ability to superimpose various symbols on the moving map display for annotation purposes is essential to use the display to its fullest advantage. The techniques described in Section IV will be used for this purpose.

5. Hologram Size

The size of the hologram in the development program was determined by the following factors:

(1) The hologram area should be at least large enough to record twice the desired resolution. This would enable the investigation of the many parameters such as color cross-talk, medium linearity efficiency, etc. without the complicating effects of operating near the medium cutoff.

(2) The hologram size choice is also subject to convenience factors such as the sizes and kinds of lenses available to set up the experiment. No special lenses were designed and fabricated since the cost would have been prohibitive; lenses were taken from stock. It is often difficult and sometimes impossible to obtain a lens with the correct diameter for a given focal length. For example, the imaging lens must have the exact design diameter in order to minimize hologram width; if the lens diameter is too small, resolution is lost; if too large, the mount occults the reference beam. The combination of lenses and hardware available resulted in a hologram diameter of 10 mm for the 6-in portion, 20 mm for the 13-in portion. The magnification was thus 16. The photoresist was not operating near its resolution limits nor was the background grating frequency at the edge of its value for limiting resolution.

An actual portable model would use a smaller hologram and correspondingly greater magnification. The object map of 12 by 12 in would be recorded at 10 line pairs/mm; the total information then is 3000 cycles along both the width and the length. The recording material would be coated on a standard 16-mm wide format. The hologram width would be 12 mm in order to allow a safety margin of 2 mm on each side. The magnification under these conditions is about 27.

B. TENTATIVE SPECIFICATION FOR A DELIVERABLE DEMONSTRATION MODEL

1.0 SCOPE

1.1 SCOPE- It has been demonstrated that holograms made of maps can be projected using white-light sources to produce a high-resolution multicolor map display. This specification covers the design requirements for a laboratory model of a holographic multicolor map display unit capable of demonstrating that standard aeronautical charts can be stored in holographic form and presented in a moving map display to be used as a navigation aid in the cockpit of an aircraft.

1.2 CLASSIFICATION - The display system shall consist of the following items:

(a) Display unit, including map hologram cassettes
(b) Power Supply Unit.

2.0 APPLICABLE DOCUMENTS

2.1 GENERAL - The following documents of the issue in effect at the date of this specification form a part of this specification to the extent specified herein:

MIL-I-6181 Interference Control Requirements, Aircraft Equipment
MIL-N-18307 Nomenclature and Nameplates for Aeronautical Electronics and Associated Equipment.

2.2 PRECEDENCE OF DOCUMENTS - The contract shall have precedence over any specification. This specification shall have precedence over any proposals or referenced specification.

3.0 REQUIREMENTS

3.1 MATERIALS, PARTS AND WORKMANSHIP - Materials, component parts and workmanship used in the construction of this system shall be in accordance with the highest grade commercial practice.

3.1.1 Microelectronic Devices - Microelectronic devices shall be used wherever feasible.

3.1.2 Modules Maintenance - The electronic portions of the system shall be divided into maintenance modules. Maintenance modules shall normally be considered repairable.

3.2 GENERAL DESIGN AND CONSTRUCTION

3.2.1 Design Objectives - The display shall be designed as a laboratory model to demonstrate the feasibility of utilizing advanced hologram techniques to present map displays to naval aircraft pilots.

3.2.2 Total Weight - The total weight of the display system excluding cables, shall not exceed eighty (80) pounds.

3.2.3 Operating Requirements - The system shall be designed to meet the following operational requirements.

3.2.3.1 Operational Stability - Equipment shall operate with optimum performance for two hundred (200) hours continuously or intermittently without the necessity for changing any adjustments which are inaccessible during equipment operation.

3.2.3.2 Total Operating Life - The equipment shall have a minimum total operating life of one thousand (1000) hours with reasonable servicing and replacement of parts.

3.2.4 Interference Control - The nature of radio interference generation is such that serious consideration must be given in the earliest practical stages of design and development so that the generation of radio interference by the equipment and the vulnerability of the equipment to radio interference shall be satisfactorily controlled within the limits of specification MIL-I-6181.

3.2.5 Standard Conditions - The following conditions shall be used as a basis to establish normal performance requirements and for making laboratory bench tests on the equipment.

Temperature:	Room ambient, 25°C + 5°C
Altitude:	Normal ground
Vibration:	None
Humidity:	Room ambient up to 90% relative humidity
Input Power:	115V ± 10V, 1φ, 60 Hz

3.2.6 Primary Input Power Requirements - Power shall not exceed 2 kVA maximum AC power (1 Phase), 115 V, 60 Hz.

3.2.7 Overload Protection - Overload protection for the equipment shall be provided in the equipment. All parts and circuits of the equipment which are likely to carry an overload due to any failure or poor adjustment shall be proportioned to withstand such overload without permanent damage to the equipment, or shall have suitable protection devices. The use of fuses and other protective devices shall be held to a minimum.

3.2.7.1 Undervoltage Protection - The unit shall not be damaged by voltage below the minimum specified herein and shall automatically resume normal operation when the voltage returns within limits.

3.2.8 Warm-up Time - The unit shall operate normally after a maximum warm-up time of five (5) minutes under standard conditions.

3.2.9 Temperature Control - There shall be no special external provision for heating or cooling the display unit.

3.2.10 Markings - The information content and format for a name plate shall be guided by the requirements of MIL-N-18307. All markings shall be of a durable nature.

3.3 PERFORMANCE - Three filtered white light sources shall provide high intensity illumination of a multicolor moving-map hologram which is projected onto a directional screen for direct viewing. One of four or more holograms stored on a film strip in a cassette shall be selectable on command of the operator. The translation (and rotation if provided) of the selected hologram display shall be under front panel manual control. Illuminance (brightness) of the display shall be variable from full brightness to zero intensity.

3.3.1 Safety Features - Every possible safety feature shall be incorporated in this system so that no personal injury or equipment damage could result from the high electrical power.

3.3.2 Suitable Interface - Suitable electrical and mechanical interfaces shall be developed between the two units of the system.

3.4 DESIGN REQUIREMENTS

3.4.1 Display Unit - The display unit shall be designed to meet the following requirements.

3.4.1.1 Function - The display unit shall be capable of presenting multicolor aeronautical chart information from storage on a holographic tape

contained in a cassette. The displayed hologram shall be as selected by an operator using front panel controls on the equipment. The displayed information shall show no degradation in color rendition or resolution from the information drawn on the original charts. The display as it appears on the screen shall be a real image of the projected hologram.

3.4.1.2 Form Factor - The display unit shall not exceed the following dimensions: 8 in H by 8 in W by 24 in L.

3.4.1.3 Weight - The weight of the display unit shall not exceed thirty-five (35) pounds.

3.4.1.4 Mounting - The display unit shall be suitable for table-top operation. In designing this unit consideration shall be given for future mounting in an aircraft instrument panel.

3.4.1.5 Control Function - Front panel controls shall be provided and identified for controlling:

(a) System ON-OFF
(b) Hologram Selection
(c) X-position
(d) Y-position
(e) Image Brightness
(f) Image rotation if applicable.

3.4.1.5.1 Index - The controlling knobs or switches shall be indexed to allow coverage over the following ranges:

(a) System power: ON or OFF
(b) Hologram Selection: Selection of 1 through 500 position. Each position shall be identifiable by a displayed member. A push button switch will be provided to initiate a search function.
(c) X-position: Suitably indexed to cover entire range of control
(d) Y-position: Suitably indexed to cover entire range of control
(e) Image brightness: Continuously controllable from "OFF" to MAXimum.

3.4.1.6 Contents of Display Unit - The Display Unit shall consist of the necessary optical power sources, display optics with associated tape drive and replaceable hologram tape cassettes to present a multicolor moving map display on a viewing screen.

3.4.1.6.1 Optical Power Sources - Three (3) filtered, white-light sources shall be used for image reconstruction. The sources shall be selected such that when used to interrogate a recorded hologram a

multicolor moving map display shall be presented with color fidelity and resolution equivalent to that of existing aerial maps.

3.4.1.6.2 Display Optics - Suitable optics shall be provided to produce an acceptable display.

3.4.1.6.2.1 Viewing Screen - The screen of the display unit shall be of an anti-reflective directional material suitable for providing a high-contrast display of the projected real hologram image. The normal viewing distance of the screen shall be from 28 to 30 inches, at that distance a minimum eye relief area of 2 inches vertically by 6 inches horizontally shall be provided.

3.4.1.6.2.2 Brightness - The screen shall have a brightness acceptable for viewing when 250 lumens per square foot are incident upon the screen from the viewing side.

3.4.1.6.2.3 Size - The size of the display area of the screen shall be six (6) inches in diameter.

3.4.1.6.2.4 Resolution - The resolution of the display as measured on the screen shall be at least ten line pairs per millimeter to the 65% response point.

3.4.1.6.2.5 Color Balance - The color balance between red, green and blue shall be within ± 10% at various levels of luminance.

3.4.1.6.2.6 Distortion - The information presented on the screen shall be free of barreling, pin cushioning, or noise distortion.

3.4.1.6.2.7 Uniform Luminance (Brightness) - The maximum allowable difference in luminance between the most bright and the least bright portion of the display shall not vary more than 10% for various levels of overall illumination when a solid color background hologram is projected on the screen.

3.4.1.6.2.8 Marking - A compass rose shall be provided (if applicable the compass shall rotate with the map rotation so that North on the map always corresponds to North on the rose). The viewing screen shall be suitably marked with a 1/4-inch diameter circle to represent "own" aircraft position in the center of the screen.

3.4.1.6.3 Transport Mechanics - A transport mechanism shall be provided which will permit the positive selection of any designated hologram stored in the cassette within one minute. Provision shall be provided to allow

continuous motion from one hologram to an adjacent hologram on the tape reel. The discontinuity between holograms shall be held to a minimum.

3.4.1.6.3.1 **Projection** - The transport mechanism shall position the map such that the map can be projected onto a viewing screen so that a 6-inch-diameter screen displays a portion of the full image. Provision for translating the image in X a distance of ± 3-1/2 inches shall be provided. The display transport shall be capable of providing continuous image translation in Y.

3.4.1.6.3.2 **Image Rotation** - An option shall be provided which will allow rotation of the displayed map above the map center. The map display shall be designed such that the image rotation option may be elected at any time during the course of the program.

3.4.1.6.3.3 **Motion Uniformity** - It shall be possible to translate (and rotate if provided) the information displayed without introducing jump, jitter, or other distracting viewing effects.

3.4.1.6.3.4 **Repeatability** - When subjected to a repeated control input value, a hologram display shall be located in a position on the screen to ± 0.10 inch in the lateral direction (and within ± 2.0 degree if rotation is provided.

3.4.1.6.3.5 **Position Detection** - An optical system shall be provided to interrogate a data block which indicates the map presented in the viewing aperture.

3.4.1.6.4 **Controlled Electronics** - Necessary electronics shall be provided to permit map selection under designation of an operator from the front panel controls.

3.4.1.6.5 **Hologram Storage** - The holograms necessary to reproduce full-color maps from filtered white light sources shall be stored on a flexible tape reeled in a cassette.

3.4.1.6.5.1 **Material** - The hologram storage medium shall consist of a material which is inexpensive and which allows inexpensive duplication from a master recording. The material will be such that it can be reeled and stored in a cassette.

3.4.1.6.5.2 Density of Packing - Each hologram shall contain information sufficient to allow the display of a square map segment 12.5 inches on a side. The size of the hologram required to store each map segment along with a digital retrieval code shall not exceed 1/2 by 1/2 inch.

3.4.1.6.5.3 Magnification - The holograms shall be made so that the 6-inch-diameter display of an aeronautical chart shall have a 4:3 magnification of scale to which the original chart was printed.

3.4.1.6.5.4 Storage Format - A minimum of four holograms repeated a number of times shall be stored on the hologram tape and shall be reeled in a replaceable transport compatible cassette (two cassettes shall be supplied with the demonstration unit). The cassette shall be designed to accommodate 500 map segments. The hologram shall be recorded such that adjacent map segments can be butted and registered.

3.4.2 Power Supply Unit - A power supply unit shall be provided containing all power supplies necessary for operation of the display unit.

3.4.2.1 Size and Weight - The power supply unit shall occupy less than 2 cu. ft. and shall weigh less than 45 pounds.

3.4.2.2 Input: 115 V, 60 Hz, single phase

3.4.2.3 Output: Power necessary for operation of the display unit.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 DESIGN APPROVAL - Design techniques used during the development of the system shall be subject to review and inspection by the Government. NAVAIRDEVCEN shall be notified in advance of salient milestones in the vendor's development schedule.

4.2 TEST PROCEDURES - The procedures and methods for conducting tests to determine compliance with the requirements of the contract, specification, and/or proposal shall be prepared by the contractor and sent to NAVAIRDEVCEN for approval. The right is reserved to modify the tests or require additional tests deemed necessary to determine compliance with the requirements of the contract, specification and/or proposals. The proposed test procedures shall be submitted in sufficient time to permit review by NAVAIRDEVCEN and all necessary revisions by the contractor prior to the start of any tests.

Appendix B

METHODS OF RECORDING AND RECONSTRUCTING HOLOGRAMS

To date this study has considered four types of holograms: (1) Fresnel, (2) Fraunhofer, (3) Fourier transform, and (4) focused image. Any of these may be formed as a surface or volume hologram with information stored as either absorption or index variations in the medium.

A. SIDEBAND FRESNEL HOLOGRAM

A Fresnel hologram is formed by the interference pattern produced between the nearfield pattern generated by an object beam derived from a coherent source and transmitted through an object transparency and a collimated reference beam derived from the same source (Fig. B-1). Formation of the hologram in this manner produces zone-lens type interference fringes on the recording medium. The reconstruction of the object is position sensitive; that is, if the holographic plate is translated, the reconstructed object is also translated. This may be likened to the positioning of a zone-lens.

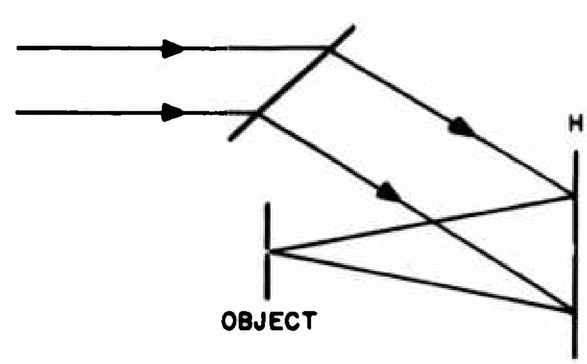


Fig. B-1. Fresnel hologram construction.

For a Fresnel hologram the diameter of this circular fringe pattern, H, determines the resolution since the smallest resolution spot size, ds, achievable is

$$ds = \frac{1.22\ \lambda\ Z_i}{H}$$

where: λ is the wavelength of light

Z_i is the distance from the hologram plate to the reconstructed image.

The spatial frequency of the zone-lens fringes recorded on the hologram increases as the distance from the center of the zone-lens increases. The maximum usable hologram size, therefore, is dictated by the film resolution, ℓ, in lines/mm; and the resolution, R_{lim}, which can ultimately be obtained in the image is given by

$$R_{lim} = 1.64\ (\ell - \alpha/\lambda)$$

where the magnification is equal to X1 and α is the angle of incidence of the reference wave with respect to the normal to the hologram.

For this type of hologram the size of the hologram plate must be large enough to capture the circular fringe pattern from the outermost resolution elements on the object. Hence, the field of view is limited by the hologram size, and ℓ_f limits the maximum theoretical resolution since it determines the usable hologram diameter. The information storage is wasteful in that the lower-order fringe frequencies, while containing little information, occupy a large area on the film surface.

One advantage of the Fresnel hologram is the relative simplicity of construction. Lenses and mirrors are not required except possibly to produce a source of quasi-monochromatic light.

B. SIDEBAND FRAUNHOFER HOLOGRAM

Fraunhofer holograms are constructed in a similar manner but are formed in the far field of the object. The line spacing of the interference fringe pattern is constant. In this case, translation of the hologram does not result in a translation of the image upon reconstruction.

Although the Fraunhofer-type hologram is formed in the far field of the object, it can also be formed with the aid of lenses which simulate the far-field conditions. This is more practical from the standpoint of system size and illuminating power requirements.

C. SIDEBAND FOURIER TRANSFORM

The Fourier transform hologram is a type of Fraunhofer hologram because the resulting fringe spacing is essentially constant. Although different configurations may be used, its basic form considered during this reporting period involved placing the object transparency at the front focal plane of a lens with the hologram formed at the back focal plane where it interferes with the reference beam derived from the main source of illumination and incident at an angle on the holographic plate. The reference wave interferes with the two-dimensional Fourier transform of the object.

The advantages and pertinent characteristics of the Fourier transform hologram are similar to the Fraunhofer hologram when conditions producing nonlinear phase terms are avoided. For this case, however, the resolution limit of the recording medium, ℓ_f, restricts the field of view, and the size of the medium determines the diffraction-limited object resolution (assuming that it is not limited by ℓ_f). Also, since lenses are used in the recording and reconstruction, demagnification may be included in the formation of the hologram.

Figure B-2 shows the construction of a point source as a Fourier transform hologram by a third method where angles θ and φ are the angles the object and reference beams, respectively, make with the normal to the holographic plate.

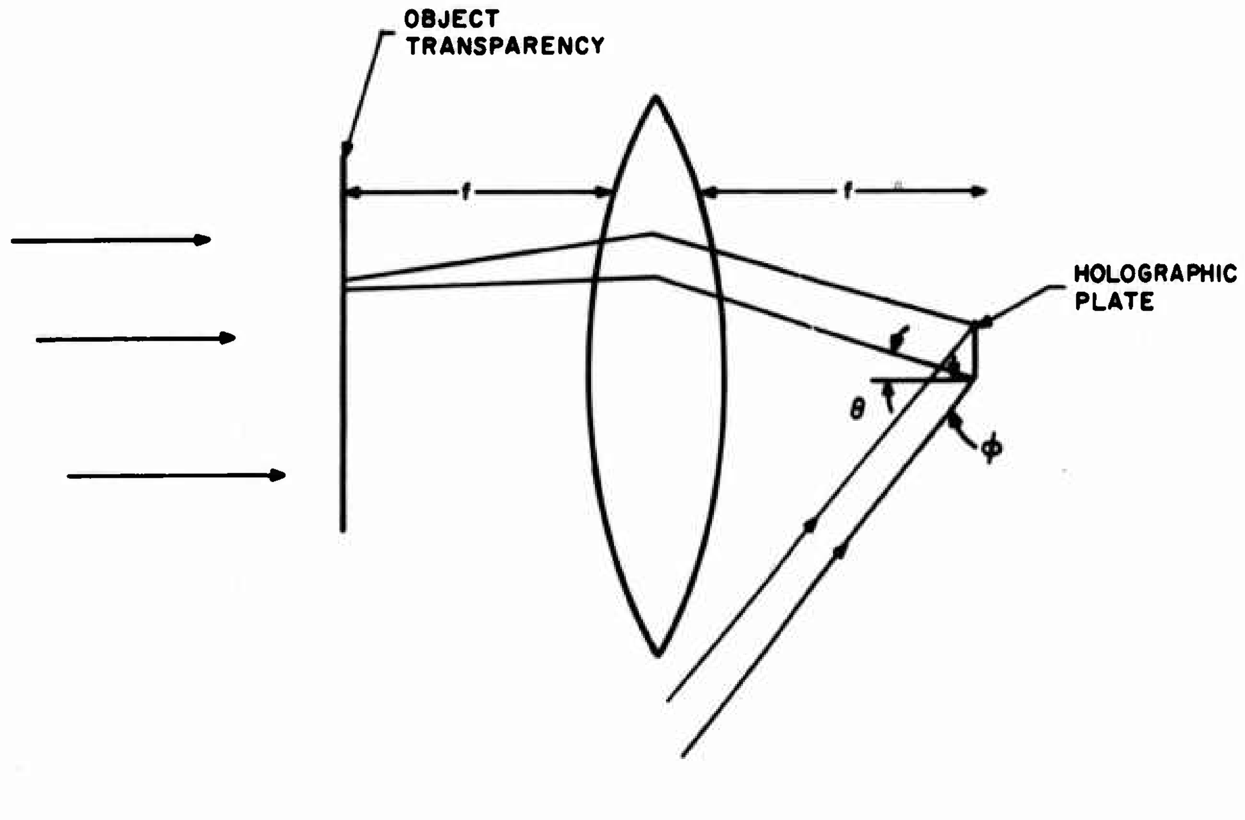


Fig. B-2. Fourier transform hologram construction.

Imperfections in the holographic media and the lenses used make it necessary to include some low order of redundancy. One possible method is shown in Fig. B-3. Here grating G is used to generate multiple object beams which introduce redundancy at the recording plane. The object transparency is placed in back of the lens, thereby reducing the final image size but also producing diverging object beams at the surface of the hologram plate and, hence, Fresnel-type fringes. The angle of these rays relative to the surface normal, limited by the hologram dimensions, determines the spatial frequency of the hologram according to

$$f_n = \frac{\sin \theta + \sin \varphi}{\lambda} .$$

and the distance $\hat{Z}$ determines the magnification of the Fourier transform at the focal plane.

An alternative arrangement is shown in Fig. B-4. Here, the location of the transparency with respect to the first lens remains the same but that lens is used merely as a collecting lens for the multiple diffracted beams from G and to demagnify the object transparency. The Fourier transforms of the object are formed in the back focal plane of lens L_2. Now, a point source on the object produces the exact Fourier transform at P_2. Note that the dc terms due to the three multiple object beams and any periodic grating structure in the object appear as bright point on the hologram plate if it is exposed at the focal plane of the lens combination. For this reason the plate is more conveniently located at a position slightly removed from the focal point or P_1. Also, it may be seen that the high frequency terms (due to small resolution points in the object) form Fraunhofer holograms whiel the dc terms produce motion-sensitive Fresnel-type zone-lenses.

D. SIDEBAND FOCUSED IMAGE HOLOGRAMS

A focused image hologram is constructed by the formation of interference fringes between an image and a reference beam. In this case, a point on the image plane is formed by converging spherical waves and hence zone-lens type fringes are formed when these interfere with the plane reference wave. As such, this is a special case of a Fresnel hologram which is motion-sensitive. The fine resolution elements appear as small Fresnel-type zone-lenses on the holographic plate.

The advantage here is that the localized distribution of the fringes decreases the effect of nonlinearity on the hologram plate and permits white-light reconstruction. The disadvantage is that scratches and dust become bothersome; therefore, it is desirable to defocus the hologram slightly from the focal plane (quasi-focused) and thereby spread the fringes over a larger area.

The obvious tradeoff between the focused and quasi-focused image hologram, therefore, involves consideration as to achievable resolution and the amount of desired redundancy.

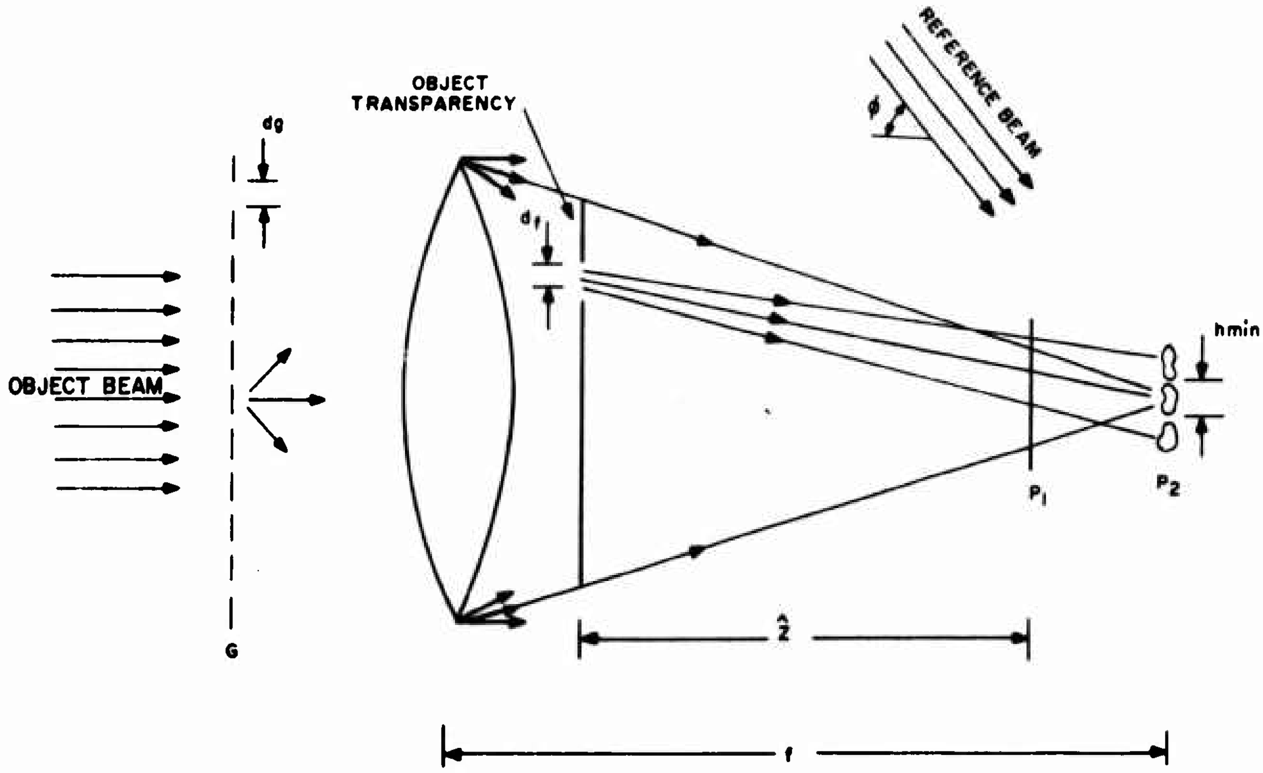


Fig. B-3. Redundancy introduction.

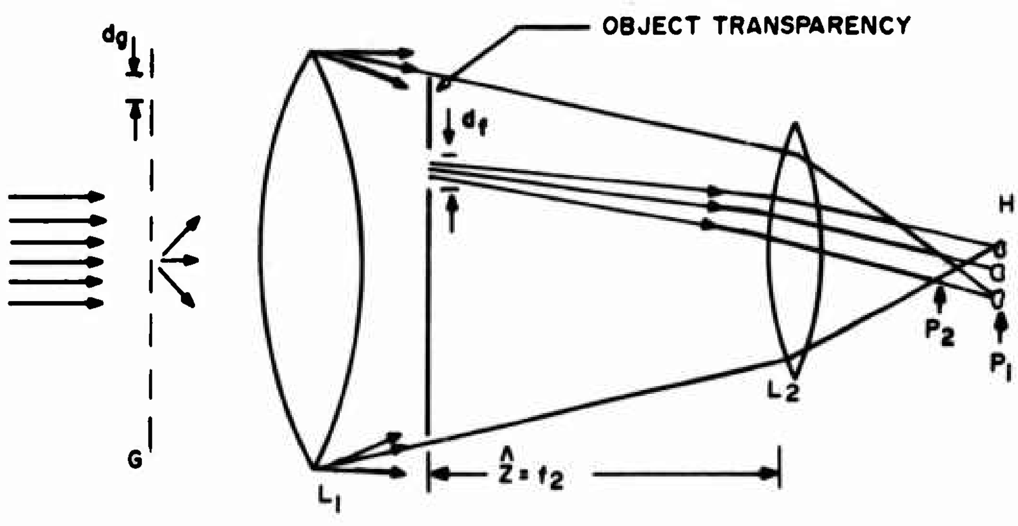


Fig. B-4. Alternative Fourier transform construction.

Appendix C

PROTOTYPE DEVELOPMENT PLAN

A plan leading to the development of the Multicolor Moving Map Display system is presented in Figure C-1. This plan shows a schedule for the development of both the display unit and the ground support equipment required to produce the holographically stored maps. The following items are included in the development schedule for the display unit.

(1) Laboratory Model - The laboratory model is a display equipment designed to present the multicolor moving map with a brightness sufficient for viewing in high ambient illumination levels. This equipment will be designed such that it can be used to provide a subjective evaluation of the display quality. The unit will be transportable and will have provisions for rotating and translating the image.

(2) Flyable Brass Board - The flyable brass board will be designed to meet the performance characteristics required of a multicolor moving map display for cockpit environment. The unit will be designed such that it can be mounted in an aircraft cockpit. It will not be constructed to meet full military specifications, but will be designed to meet all specifications related to air flight safety.

(3) Service Test Model - Several service test models may be provided which are designed and tested to meet full military specifications and may be utilized for operational evaluation.

In addition to the above equipments, ground support equipment for generating and duplicating the holograms must be developed. The field recorder (holographic generation) unit will be required to produce holograms of aerial charts from color separations on photoresist and to produce from the photoresist originals, nickel masters which are used in the duplication process.

A dual program is proposed for the development of the duplication equipment. This unit is that equipment which extracts individual map chips from storage, transfer the map chips to an embossing unit and precisely emboss the information on to vinyl tape strips. In the first phase of this development program, a deliverable brass board will be constructed. The second phase provides for the construction of a service test model.

Upon completion of the development of the three service test models (i. e., the display unit, the field recorder and the duplication unit), and upon final evaluation of these units, production prototype display and duplication units will be constructed.

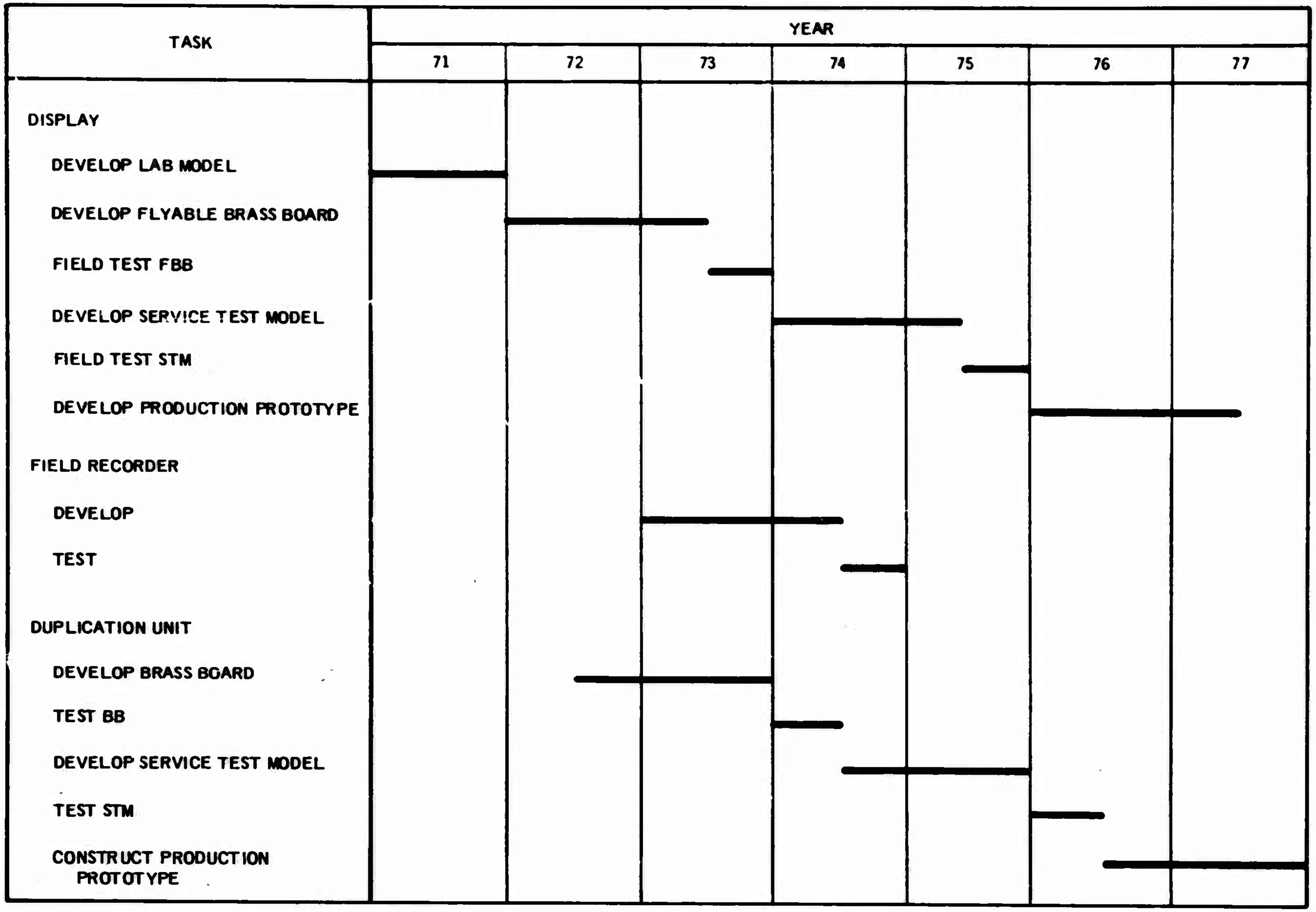


Fig. C-1. Plan and schedule for development of prototype equipment.

Appendix D

CONTRACT DEMONSTRATIONS

A. DEMONSTRATION A

The feasibility of holographically recording aeronautical charts was first demonstrated to NADC on 5 April 1970. At this time the restoration of a focused image silver halide hologram was shown. The absorptive hologram was restored in a transmission mode with the 0.4416 μm line of a HeCd laser and projected on a diffuse screen. The resolution of the displayed image was in excess of 20 line pairs/mm.

The same hologram was also restored in a transmission mode by a 48-watt tungsten white-light source. Under these conditions the restored non-chromatic image was no longer speckled as it was when coherently generated; however, the image was not viewable in high ambient light.

The translation of the map in both X and Y directions was also demonstrated.

B. DEMONSTRATION B

The restoration of a full color, holographically stored, aeronautical chart was demonstrated on 20 August 1970. The holograms shown were of the quasi-focused image type, recorded on photoresist, and restored in the reflection mode by using three filtered white-light sources. The use of spatial filtering and the predispersion of the restoration lights was compared to band-pass filtering of the same sources. The advantages of the predispersion were observed.

The importance of a screen having a low reflectivity was demonstrated by comparing the image contrast obtainable with a diffuse screen versus that obtainable with a transparent lenticular screen on a high ambient illumination. The backscatter from the diffuse screen decreased the image contrast to an unsatisfactory level while there was no noticeable backscatter from the lenticular screen. A specially made transmission phase hologram was also demonstrated as a directional screen having a high resistance to ambient illumination.

Map motion in X and Y directions was demonstrated and the capability for image rotation was shown. A data block, overlaid on a hologram of a color map, was restored and the motion immobility of the data block restoration was demonstrated as the hologram of the map was translated.

BIBLIOGRAPHY

1. J. H. Altman, "Pure relief images on type 649-F plates," Applied Optics, vol. 5, p. 1689, Oct. 1966.

2. H. Han[illegible]s, "Interferometric measurements of phase structures in photographs," JOSA, vol. 58, p. 141, Jan. 1968.

3. A. K. Rigler, "Wavefront reconstruction by reflection," JOSA, vol. 55, p. 1693, Dec. 1965.

4. D. H. McMahon and A. R. Franklin, "Efficient, high quality, R-10 bleached holographic diffraction gratings," Applied Optics, vol. 8, p. 1927, Sept. 1969.

5. M. Young and F. H. Kittredge, "Amplitude and phase holograms exposed on Agfa-Gevaert 10E75 plates," Applied Optics, vol. 8, p. 2353-54, Nov. 1969.

6. T. A. Shankoff, "Phase holograms in dichromated gelatin," Applied Optics, vol. 7, p. 2101, Oct. 1968.

7. N. K. Sheridan, "Production of blazed holograms," Applied Physics Letters, vol. 12, no. 9, p. 316.

8. Close et al., "Hologram recording on photopolymer materials," Applied Physics Letters, p. 159, March 1969.

9. A. A. Friesem and J. L. Walker, "Experimental investigation of some anomalies in photographic plates," Applied Optics, vol. 8, p. 1504, July 1969.

10. L. H. Lin et al., "Multicolor holographic image reconstruction with white light illumination," Bell System Tech. J., vol. 45, p, 659, 1966.

11. A. A. Friesem and R. J. Fedorowicz, "Recent advances in multicolor wavefront reconstruction," Applied Optics, vol. 5, p. 1085, June 1966.

12. J. C. Urbach and R. W. Meier, "Properties and limitations of hologram recording materials," Applied Optics, vol. 8, p. 2269, Nov. 1969.

13. H. J. Gerritsen et al., "Elimination of speckle noise in holograms with redundancy," Applied Optics, vol. 7, p. 2301, Nov. 1968.

14. J. B. DeVibs and G. O. Reynolds, Theory and Application of Holography, Addison-Wesley, 1967.

15. J. W. Goodman, Introduction to Fourier Optics. New York: McGraw-Hill, 1968.

16. J. C. Urbach and R. W. Meier, "Thermoplastic xerographic holography," Applied Optics, vol. 5, p. 666, April 1966.

17. G. B. Brandt, "Image plane holograph," Applied Optics, vol. 8, no. 7, pp. 1421-29.

18. RCA News Release at David Sarnoff Research Laboratories, Princeton, N.J., Sept. 30, 1969.

19. Hassis et al., "Copying holograms," Applied Optics, vol. 5, p. 665, April 1966.

20. W. Hannan, "Elimination of Speckle Noise in Holograms with Redundancy," Applied Optics, vol. 7, p. 2301-2311, (1970)

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13. ABSTRACT

This report describes the results of the work performed under an exploratory development program designed to establish the techniques required to present a multicolor moving map display to a pilot in an aircraft cockpit environment. A system for producing a full color display 6 inches in diameter with the provision for translating and rotating the image has been postulated and its feasibility demonstrated. Methods of presenting symbols on the display have also been postulated.

During the course of the program, a holographic recording technique was selected which allowed playback of the information using white light sounds. A storage material was selected and a large volume duplication technique described. Tradeoffs were established to define the optimum method for providing display motion and symbol insertion.

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